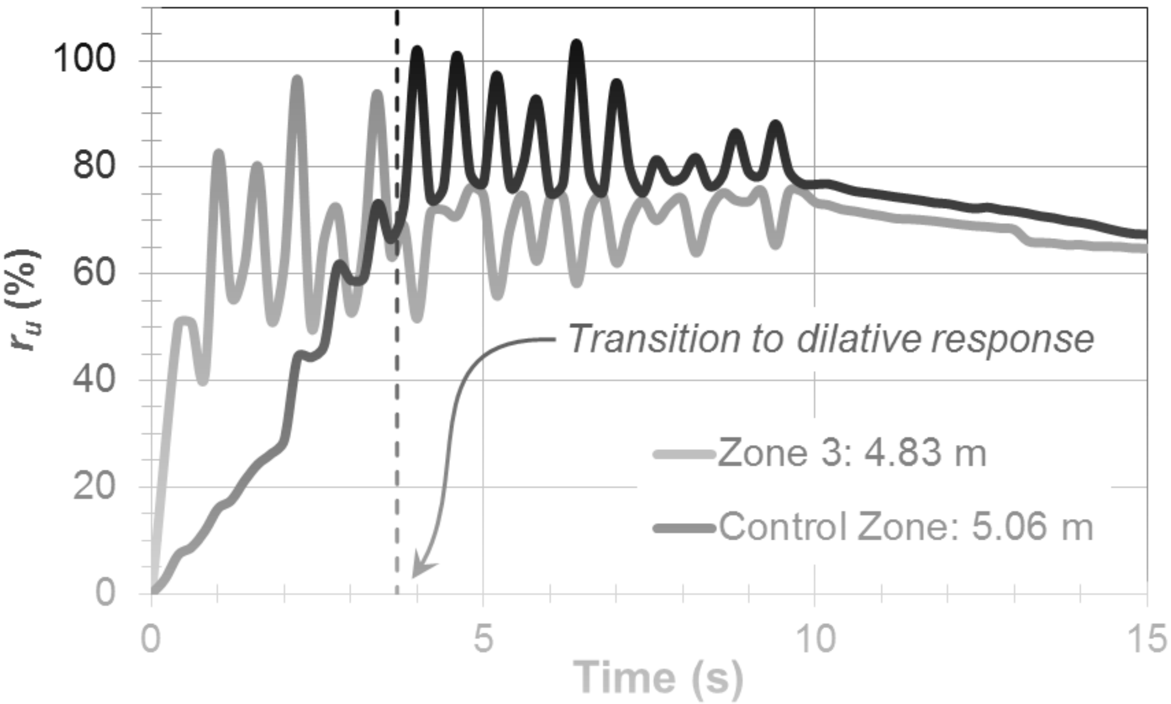
Ground Improvement and Liquefaction Mitigation using Driven Timber Piles



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14 September 2016

TRB IDEA Program: NCHRP 180 & SC Chapter: Pile Driving Contractors Association

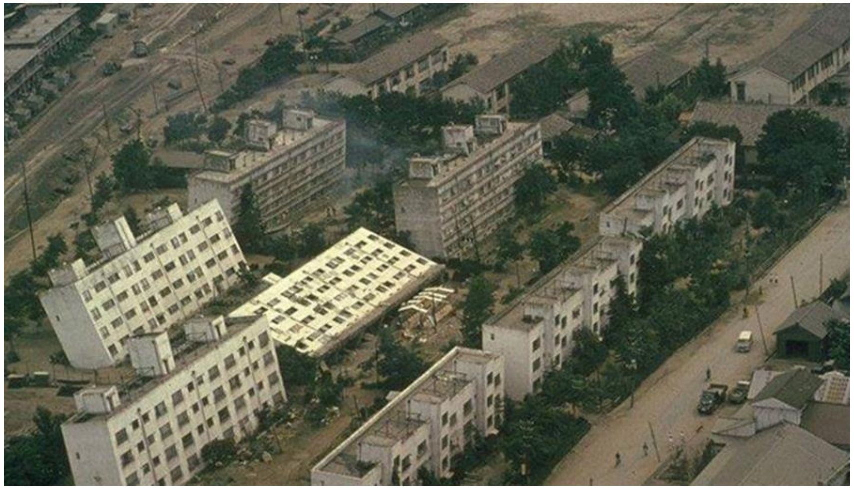
Presentation Outline

- Introduction and motivation
- Research program
- Experimental field test program
  - Selection and characterization of test site
  - Ground improvement test program in-situ tests
  - Controlled blasting program
- Numerical and Analytical Investigation
- Summary and Conclusions

Introduction and Motivation

- Liquefaction-susceptible soils: saturated, loose to medium dense, granular and slightly plastic soils
- Earthquake-induced ground motions, if strong enough or if providing sufficient number of shear stress cycles, can produce liquefaction
- Definition (with excess pore pressure): $r_u = \frac{u_e}{\sigma'_{vo}} = 1.0$

  Note: this definition not quite correct…!
- Consequences of liquefaction:
  - Flotation of underground structures
  - Excessive settlement and tilting of structures
  - Ground failure: lateral spreading, flow failure

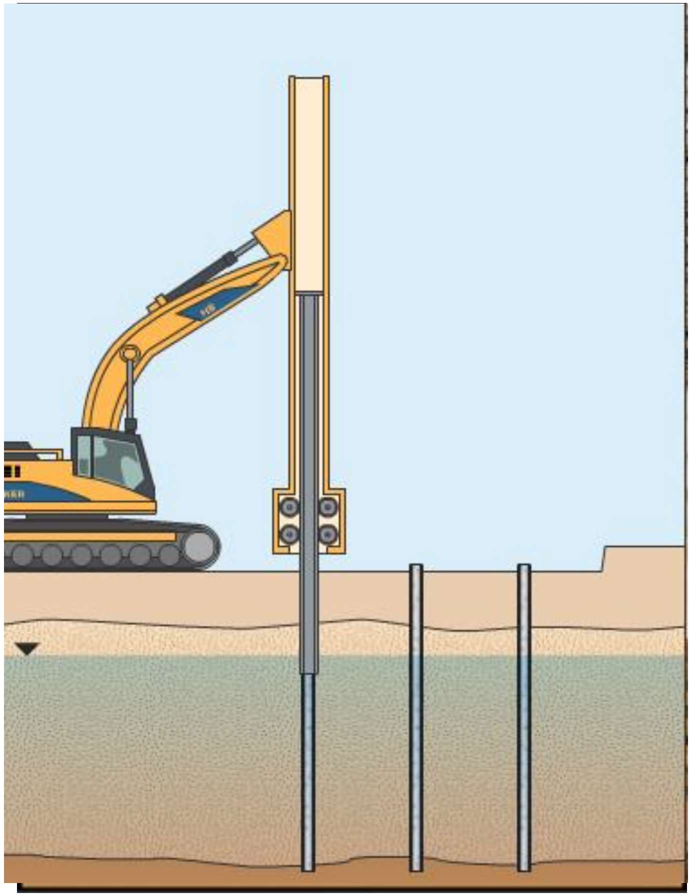


National Geophysical Data Center, 2012

Introduction and Motivation

Ground Improvement Methods

- **Densification**
  - vibro-compaction and vibro-replacement (stone columns)
  - dynamic compaction
  - compaction grouting
  - blasting
  - displacement piles
- **Reinforcement**
  - vibro-replacement (stone columns)
  - deep soil mixing / jet grouting
  - driven piles or drilled shafts
- **Drainage**
  - earthquake drains
  - stone columns (?)



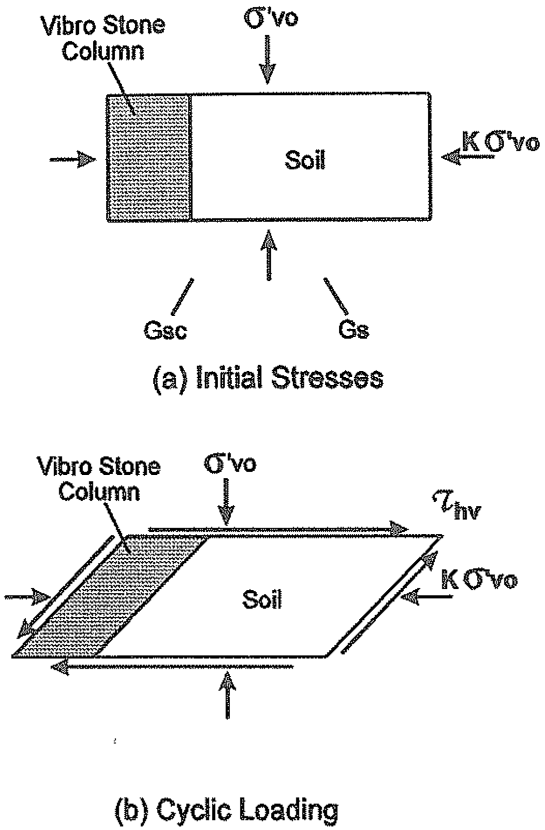
Courtesy of Hayward Baker Inc., 2014

Outstanding Questions: Densification?

- Plantema and Nolet (1957), Meyerhof (1959), Broms (1966):
  - Showed that displacement piles effectively densified granular soils
  - Loose sand densified 3.5 to 5 pile diameters away from the pile
  - Cone tip penetration resistance increased up to 2x near the pile following installation
- Some Dutch recommendations exist w/r/t densification, but for settlement of adjacent buildings, not liquefaction
- Questions include:
  - Effect of pile spacing on magnitude of densification ?
  - Effect of time ?
  - Magnitude of excess pore pressure reduction ?

Outstanding Questions: Reinforcement (?)

- Reinforcement effect – two modes
  - Vertical support and shear reinforcement: global stability
  - Stiffened elements divert the cyclic stresses away from soils, reduce u_e
- Baez (1995):
  - Introduced a theory of seismic shear stress redistribution for stone columns
  - Shear strain compatibility (**SSC**) assumption
- SHRP2: use **SSC** for CFA piles, deep soil mixing, jet grouting, vibro-concrete columns
- Olgun & Martin (2008); Rayamajhi et al. (2014):
  - Performed finite element modeling on discrete columns
  - Showed that the shear strain compatibility assumption may not be valid…
- Does the reinforcement effect result in a reduction of excess pore pressures ?



(after Baez 1995)

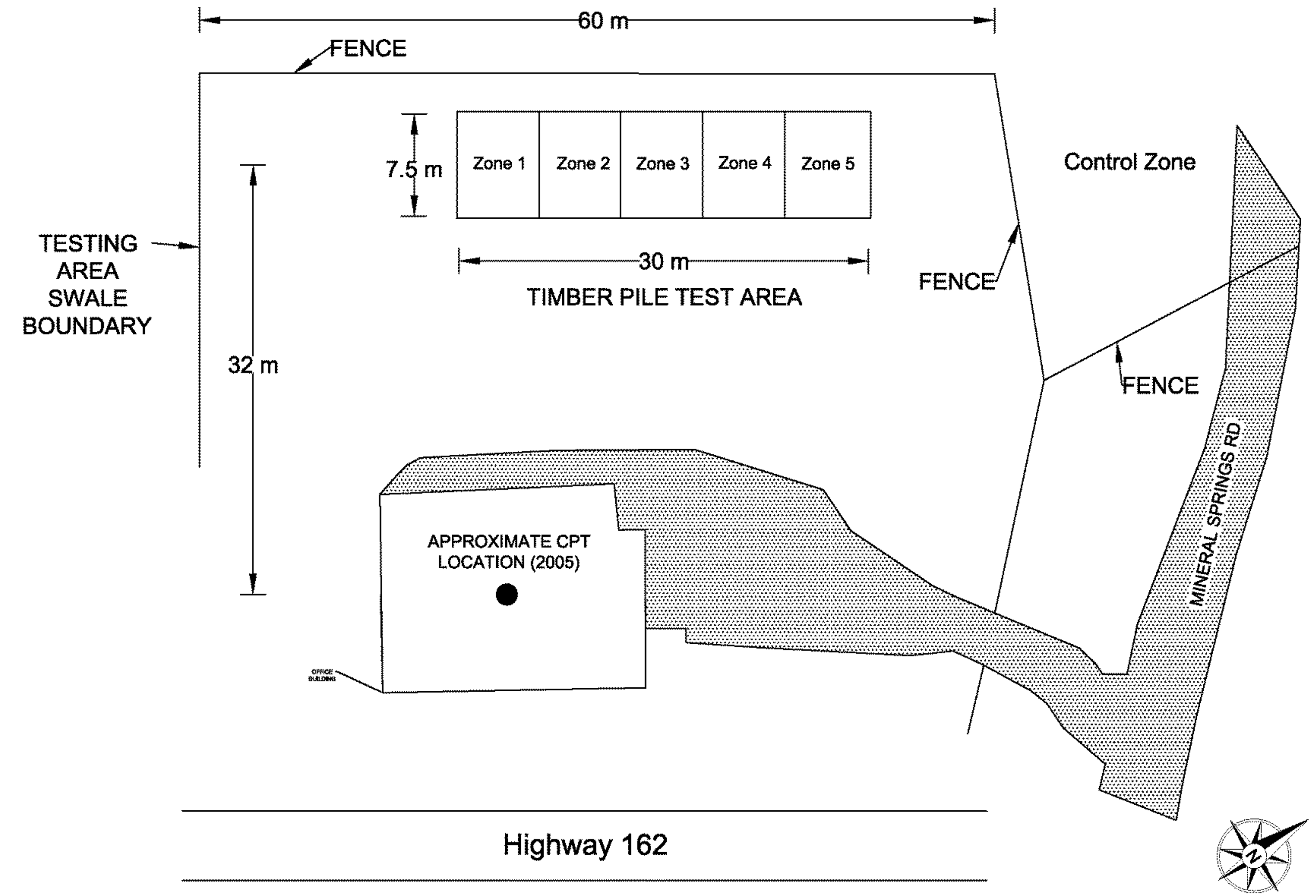
Full Scale Field Test Program and Modeling

- Compare densification and reinforcement effects of drained and conventional piles with respect to pile spacing, drainage, and time elapsed since installation;
- Evaluate the generation and dissipation of excess pore pressures and subsequent post-liquefaction settlements from controlled blasting program;
- Calibrate a finite element model to the response of an unimproved control zone; make true predictions of the excess pore pressure response treated ground; and,
- Assess the efficacy of the reinforcement effect w/r/t shear strain compatibility (***SSC***) assumption.

[Experimental Setup and In Situ Tests]

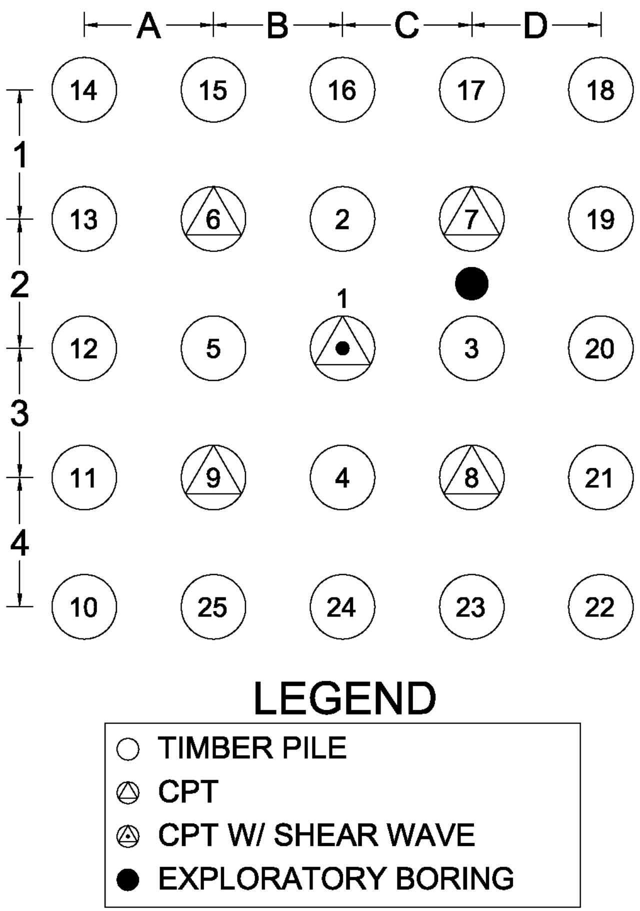
Test Site Characterization

Location: Hollywood, SC – Pile Drivers, Inc.



Test Site Characterization

- Baseline in-situ testing in each of five treated zones
  - CPTu's in each treatment zone at Piles 1, 6, 7, 8, and 9
  - Shear wave velocity tests in the center of each zone (Pile 1)
  - SPT between Piles 3 and 7
- Baseline in-situ testing in control zone
  - One CPTu (P-1); and
  - One SPT in the center

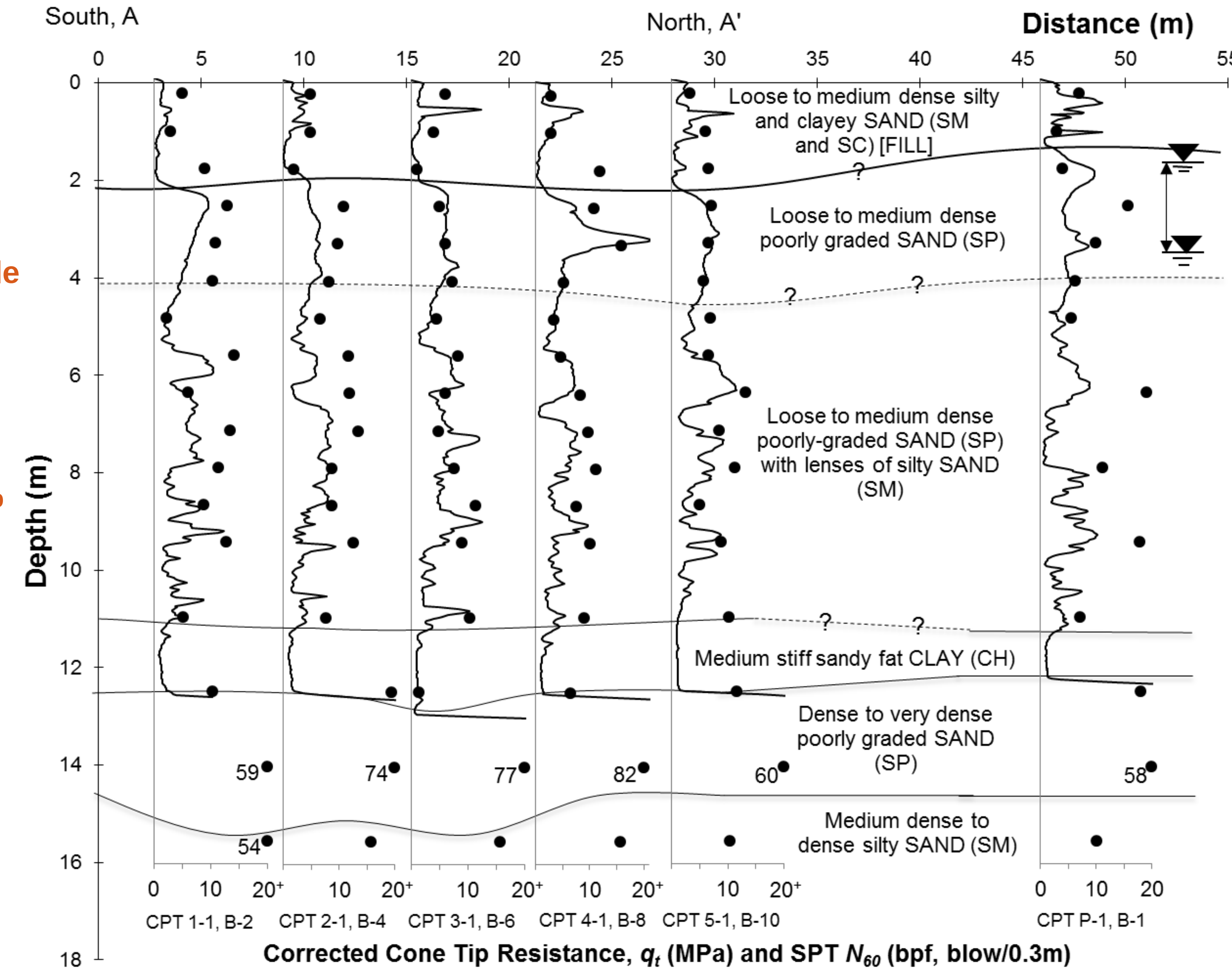


Test Site Characterization

Subsurface Profile and Identification of Liquefiable Layer

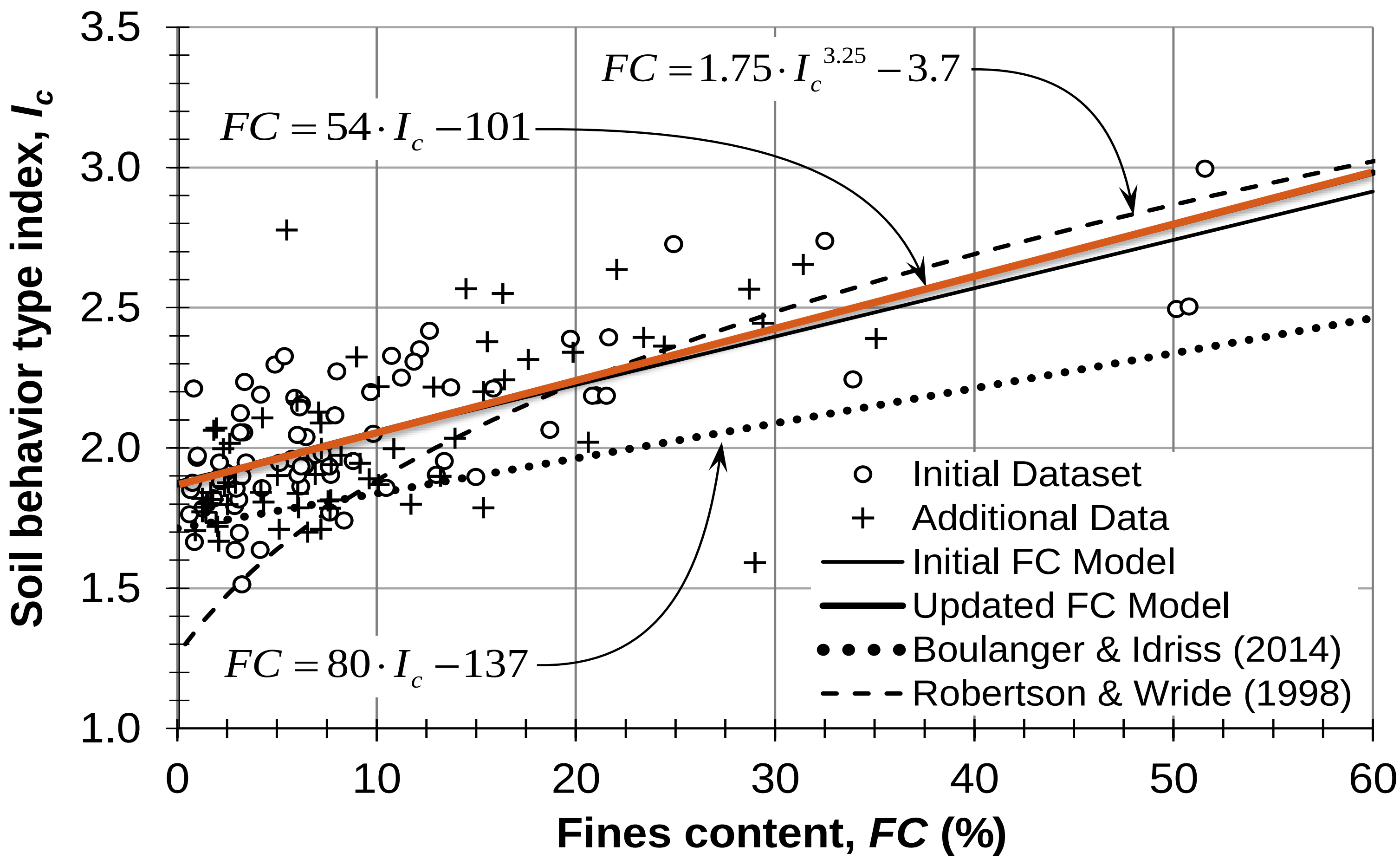
Liquefiable Soils

Initial relative density: 40 – 50%



Test Site Characterization

Fines Content correlation for Coastal Plain Beach Sands of South Carolina



$$I_c = \left[\left(3.47 - \log(Q)\right)^2 + \left(\log(F) + 1.22\right)^2 \right]^{0.5} \quad Q = \left(\frac{q_c - \sigma_{vo}}{P_a} \right) \left(\frac{P_a}{\sigma'_{vo}} \right)^n \quad F = \left(\frac{f_s}{q_c - \sigma_{vo}} \right) \cdot 100$$

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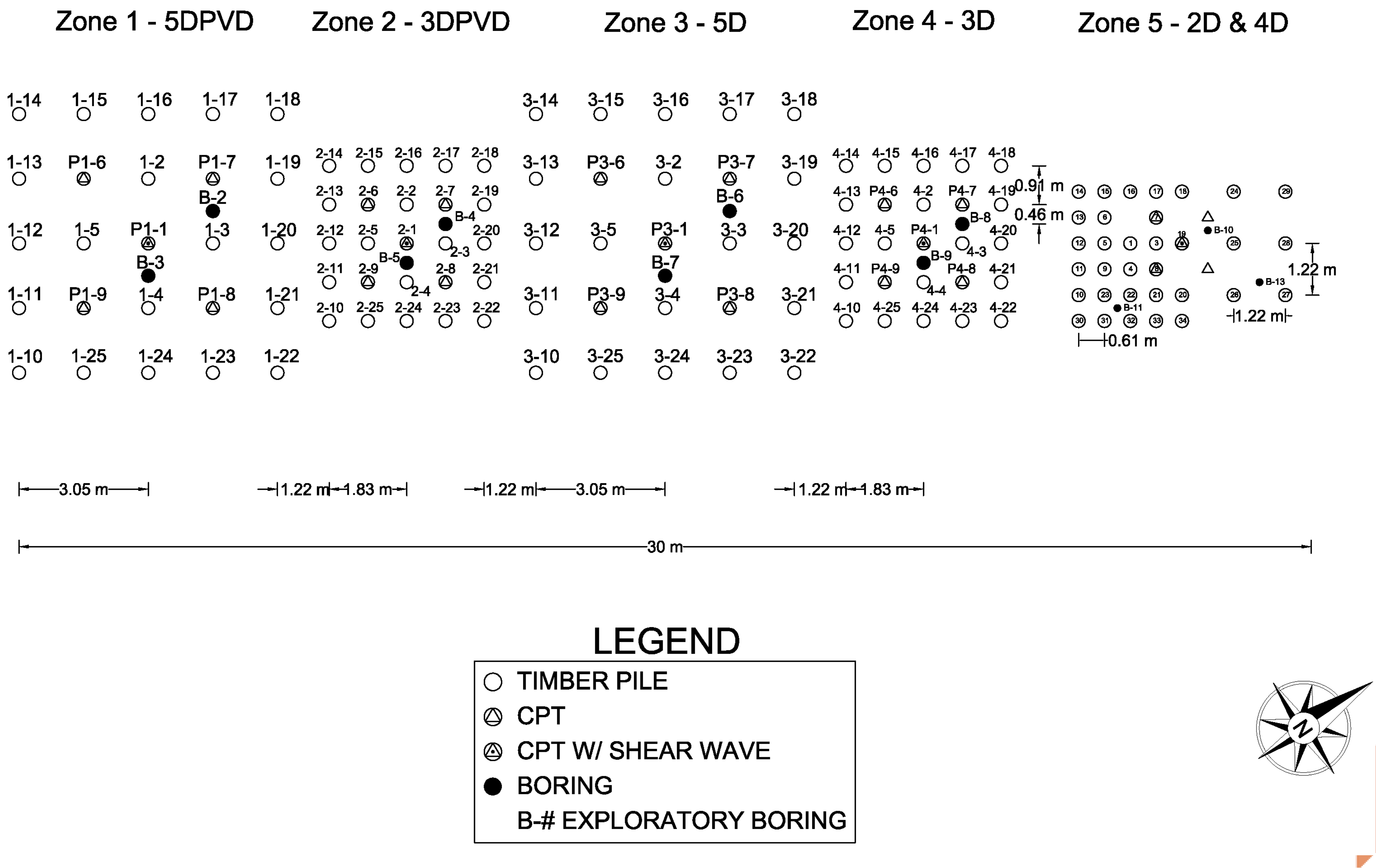
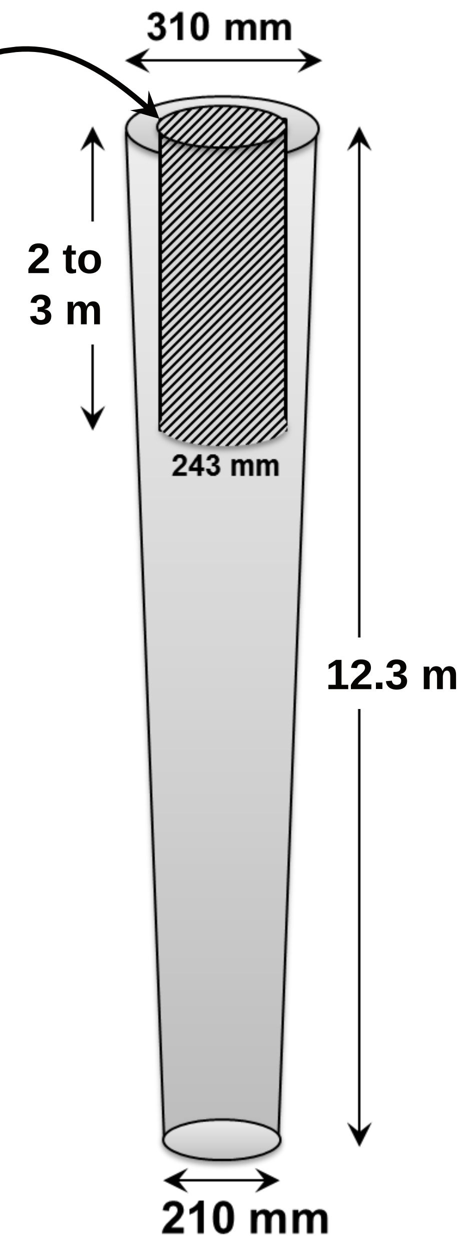
Test Pile Layout and Experimental Program



Full Scale Field Test Program: Installation

Pre-drilling and spudding through fill

	Pile length (m) [feet]	Head Diameter (m) [inches]	Toe Diameter [inches]
Average	12.3 [40.3]	0.31 [12.2]	0.21 [8.3]

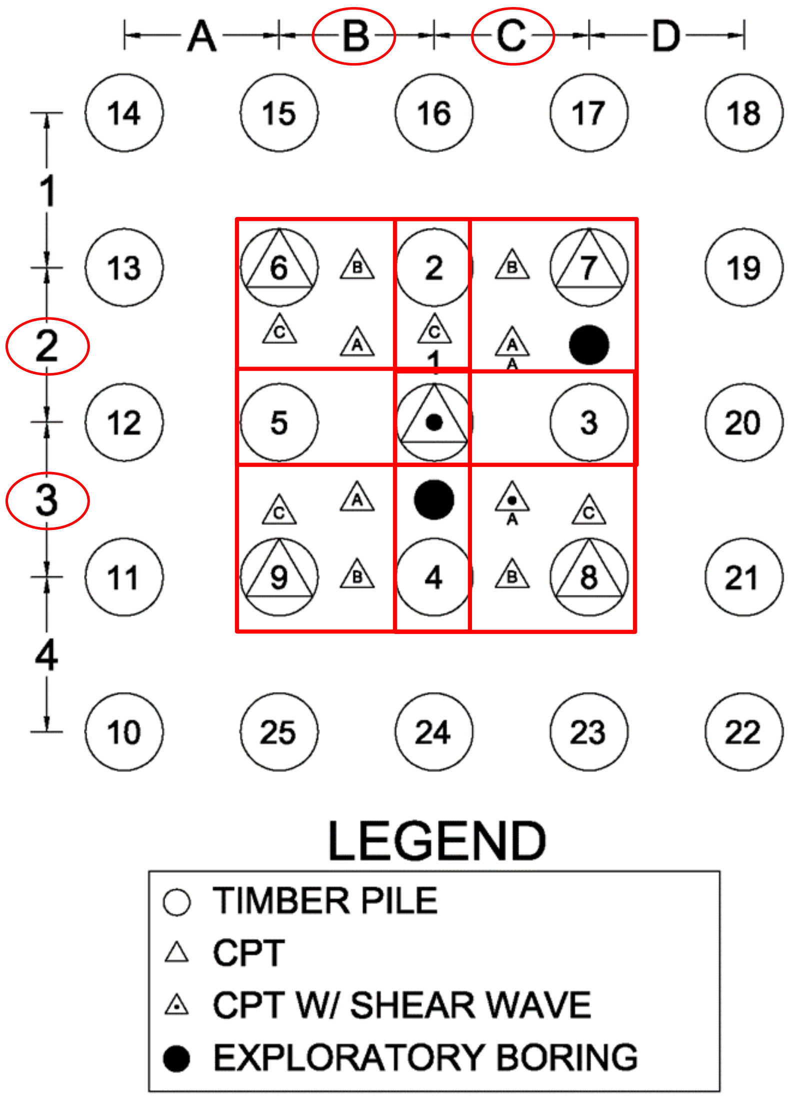


Drained Timber Pile Prototype

- Holtz and Boman (1974): PVDs fixed to timber piles reduced driving-induced positive excess pore pressures generated within soft clay
- Rollins et al. (2006; 2009): PVDs between stone columns improved densification in silty sands
- Millport Slough Replacement Bridge, US 101; PVDs between driven displacement piles improved q_t substantially
- Driving-induced *contractive* excess pore pressures should be reduced if drainage can be provided, improving densification in silty sands

Drained Timber Pile Prototype

Investigation of Densification: In-situ Tests

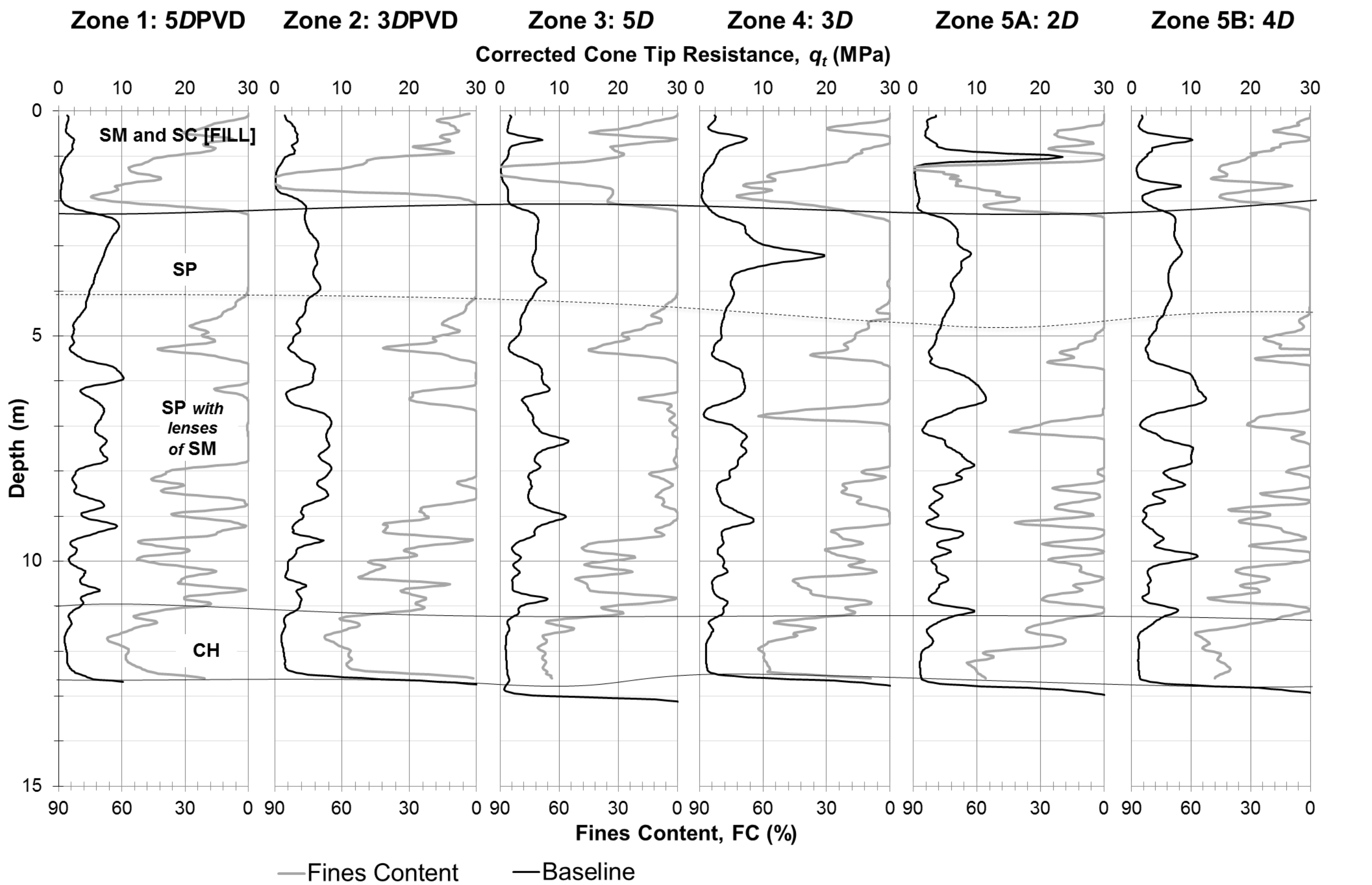


CPT testing

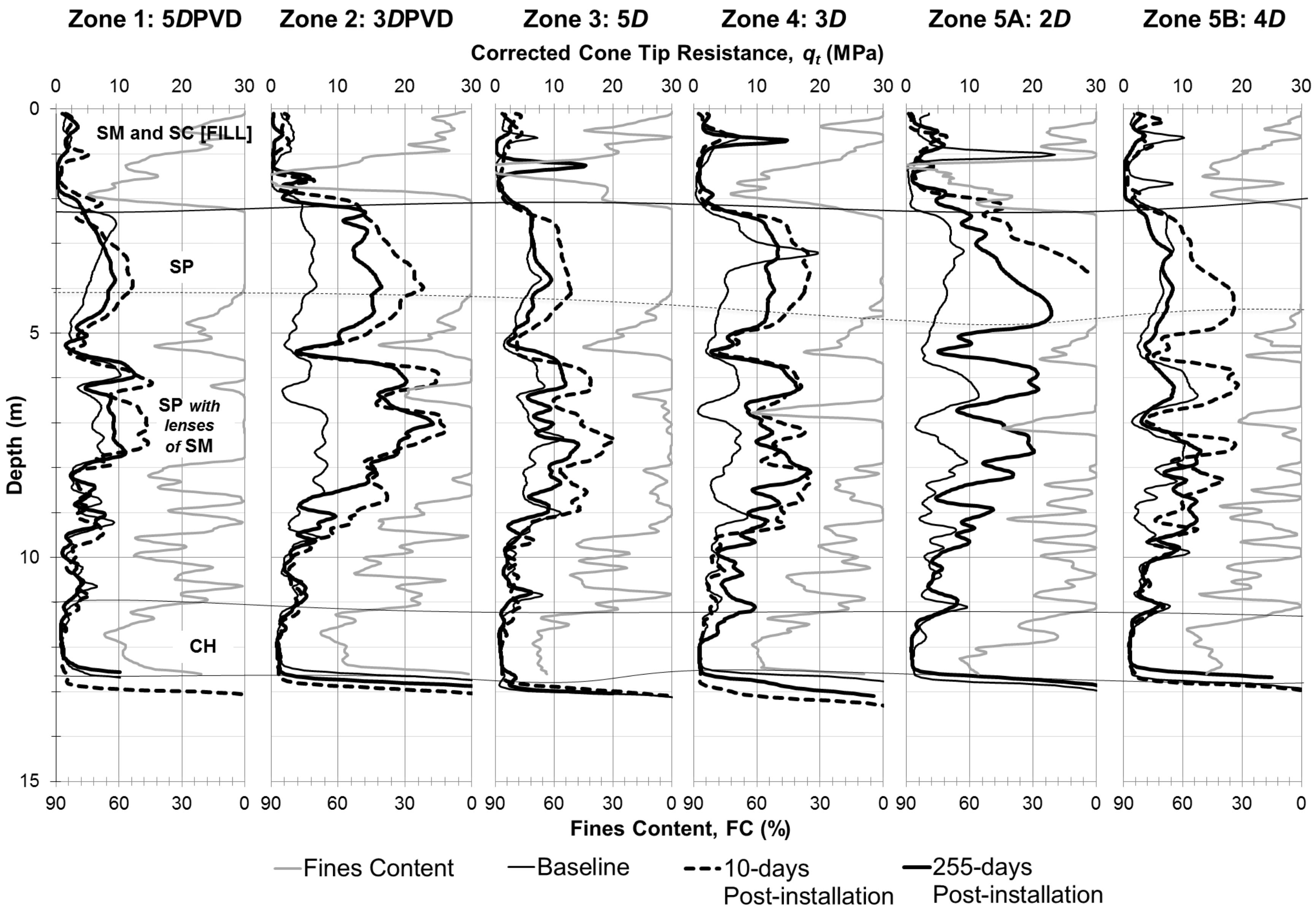
Time Following Installation	Cell Locations (Zones 1 through 4)
10 days	B2
49 days	B3
115 days	C2
255 days	C3

- Shear wave velocity test was performed at sounding A in cell C3
- SPT between Piles 1 and 4

Investigation of Densification: Cone Tip Resistance



Investigation of Densification: Cone Tip Resistance



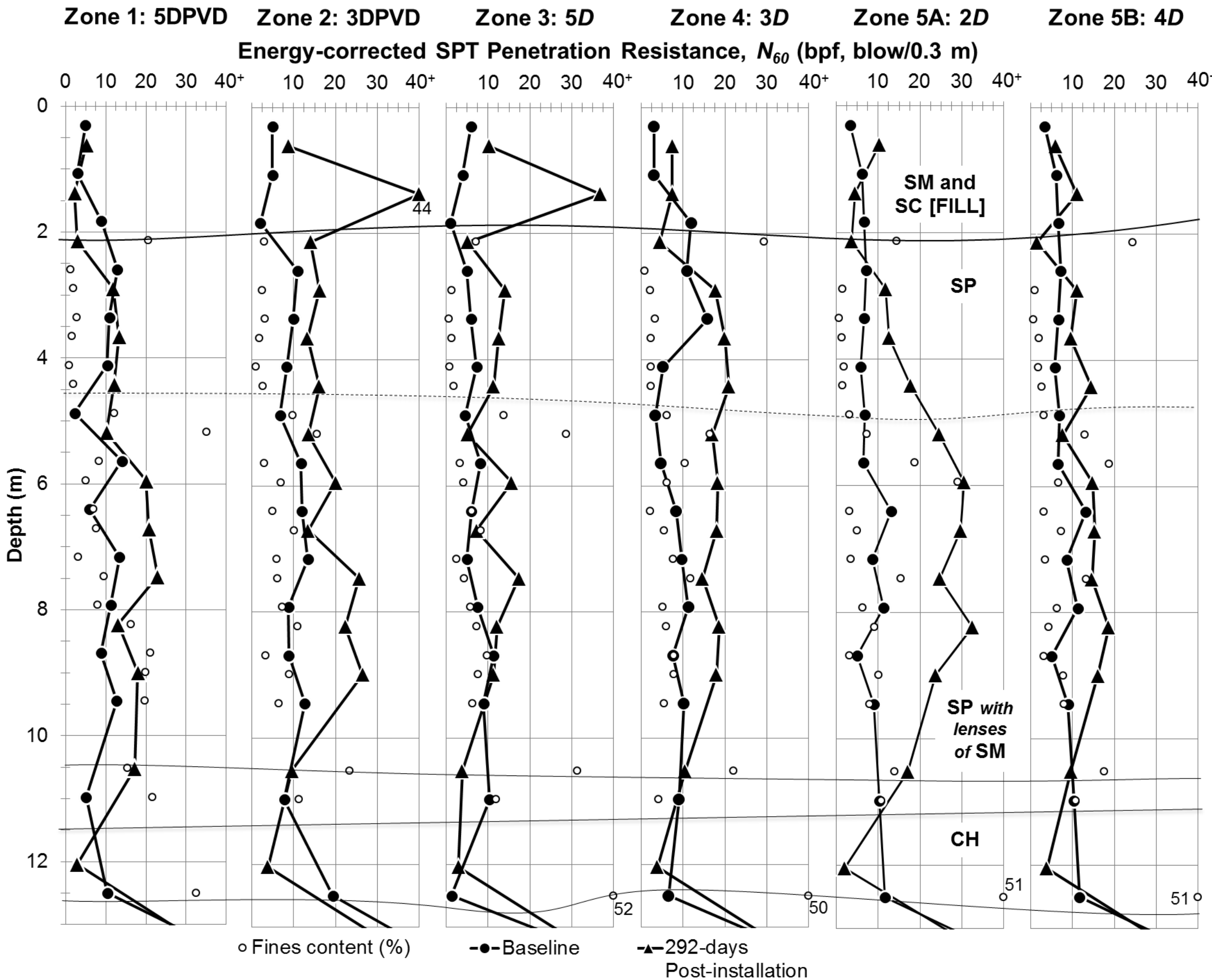
Investigation of Densification: Cone Tip Resistance

Quantitative Summary of the Liquefiable Layer

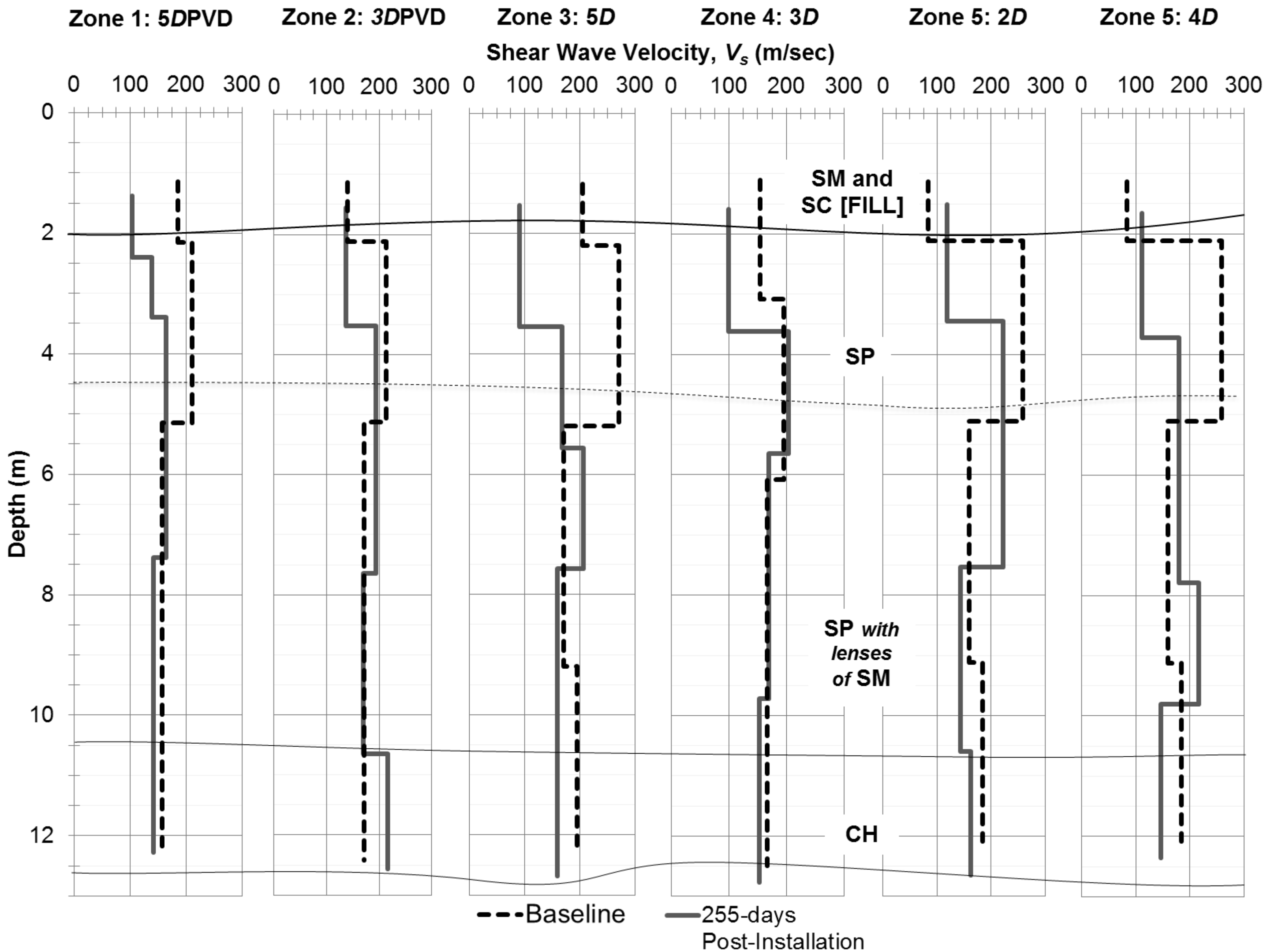
*q_t averaged over "**average toe depth of inner piles**"*

Pile Spacing	Treatment Zone #	Average Toe Depth, Inner Piles (m)	Pre-treatment Geometric Average of q_t (MPa)	10 Days Post-Installation		255 Days Post-Installation	
				Post-treatment Geometric Average of q_t (MPa)	Change in q_t (%)	Post-treatment Geometric Average of q_t (MPa)	Change in q_t (%)
5*D* PVD	1	12.1	5.23	7.55	44	6.14	18
5*D*	3	11.7	5.35	10.07	88	6.81	27
4*D*	5B	10.6	5.89	11.02	87	6.95	18
3*D* PVD	2	9.3	5.43	17.65	225	14.34	164
3*D*	4	11.1	5.22	12.21	134	10.52	102
2*D*	5A	10.6	5.60	19.76	253	13.23	136

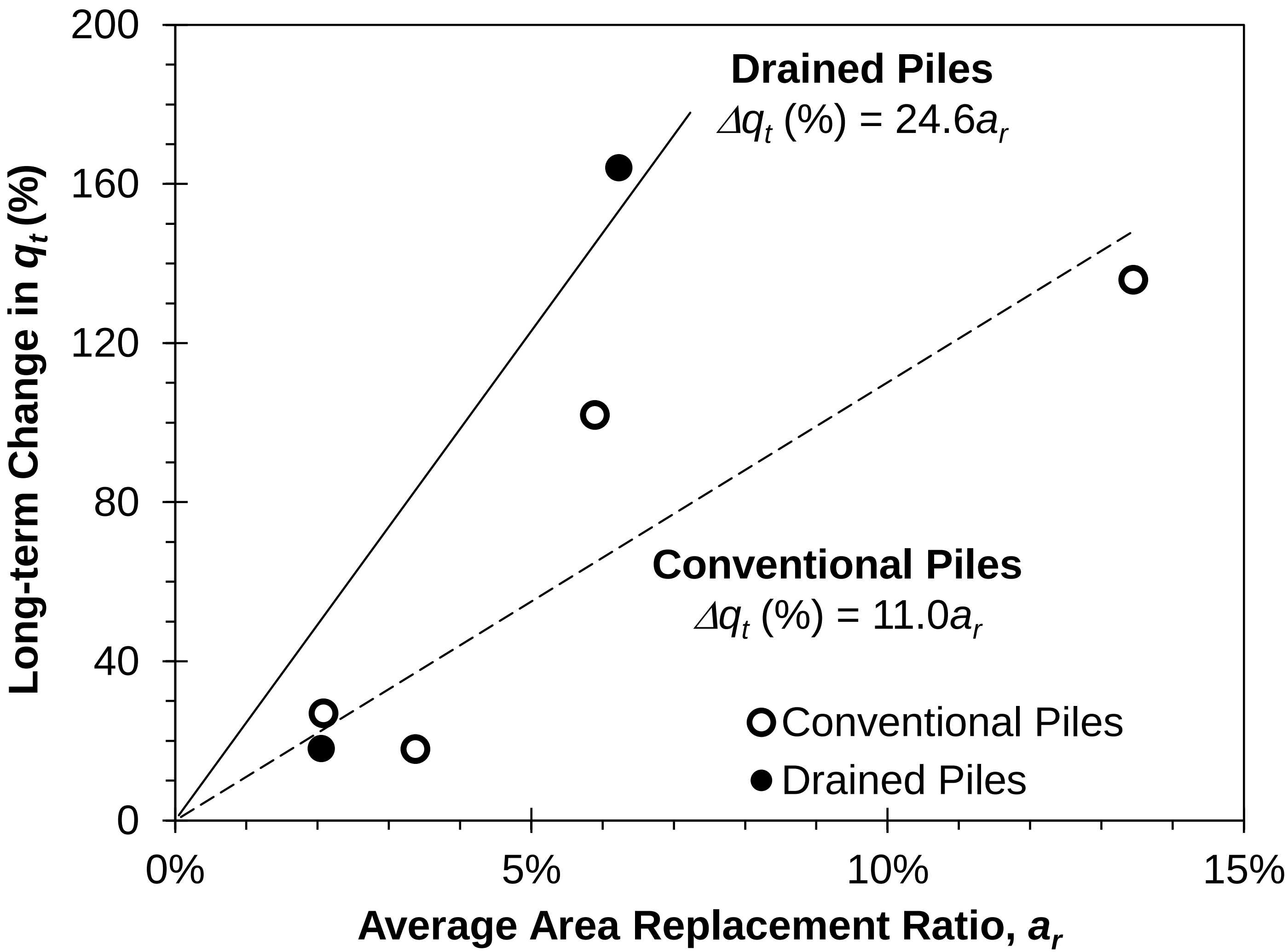
Investigation of Densification: SPT N Blow Count



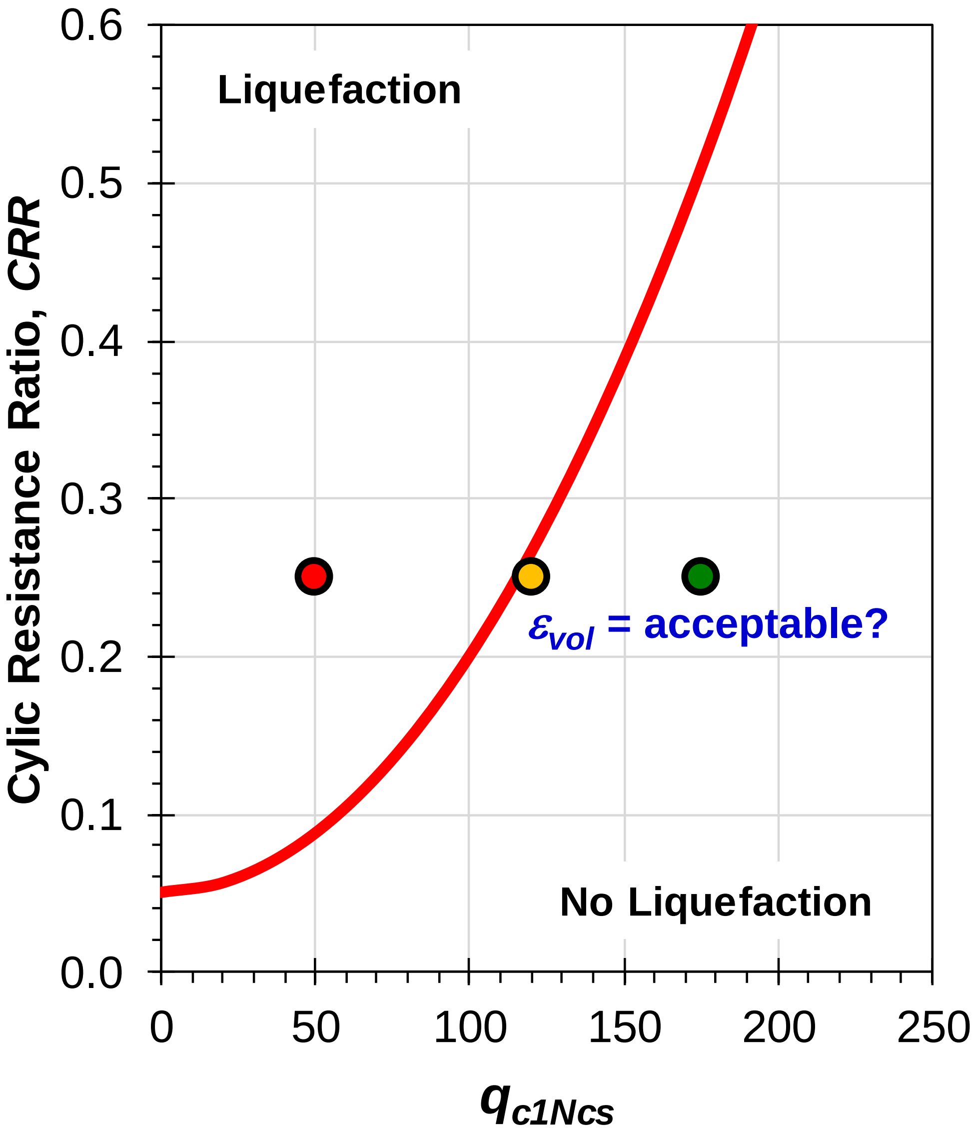
Investigation of Densification: Shear Wave Velocity



Summary: Average Improvement in CPT q_t



Application to Liquefaction Mitigation



- Conduct triggering analysis for liquefiable layer(s)
- Select spacing (area replacement ratio) and estimate densification (i.e., Δq_{c1Ncs})
- Re-evaluate triggering analysis as needed to select final design spacing
- Conduct post-densification *in situ* tests to confirm design assumptions

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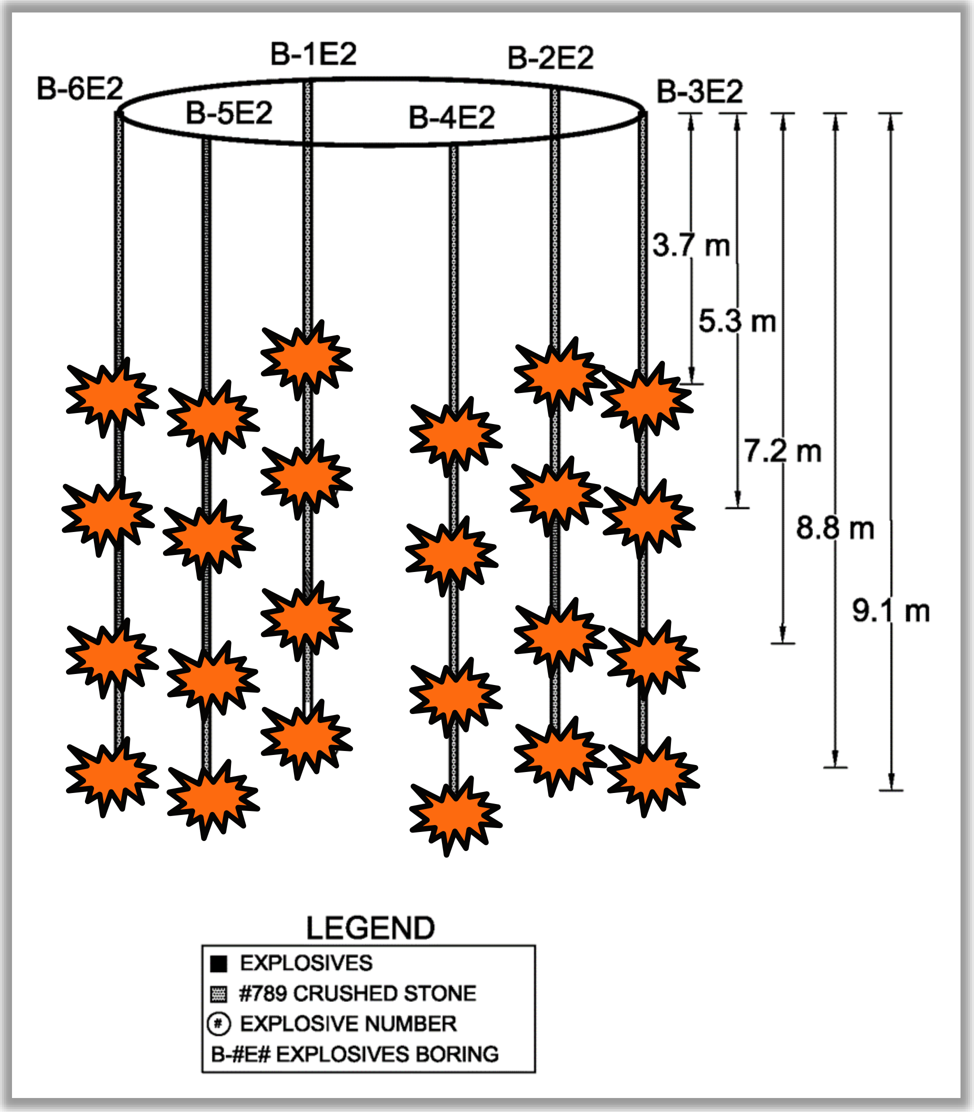
[Controlled Blasting]

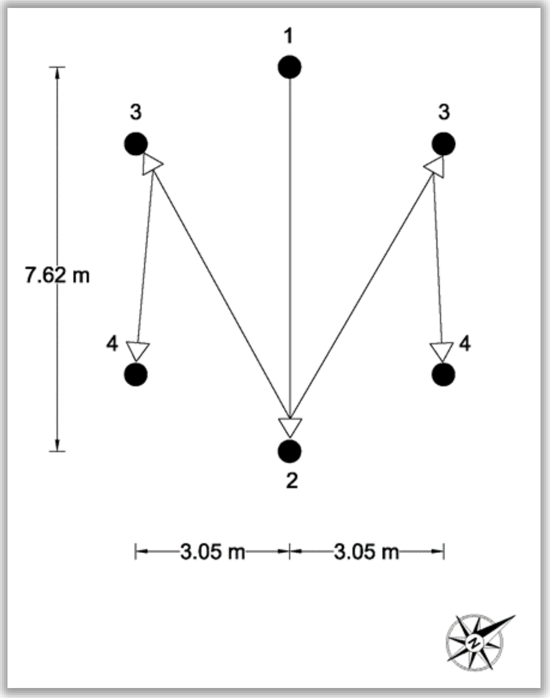
Liquefaction Assessment and Mitigation

Controlled Blasting Program:

- Install pore pressure transducers to observe blast-induced excess pore pressures, perform baseline survey
- Evaluate explosive charge weight and blast sequence req'd to induce liquefaction in unimproved control zone
- Apply same charge weight and sequence to timber pile treated zones
- Compare excess pore pressures generated from blast program
- Compare ground settlements resulting from reconsolidation and dissipation of excess pore pressures

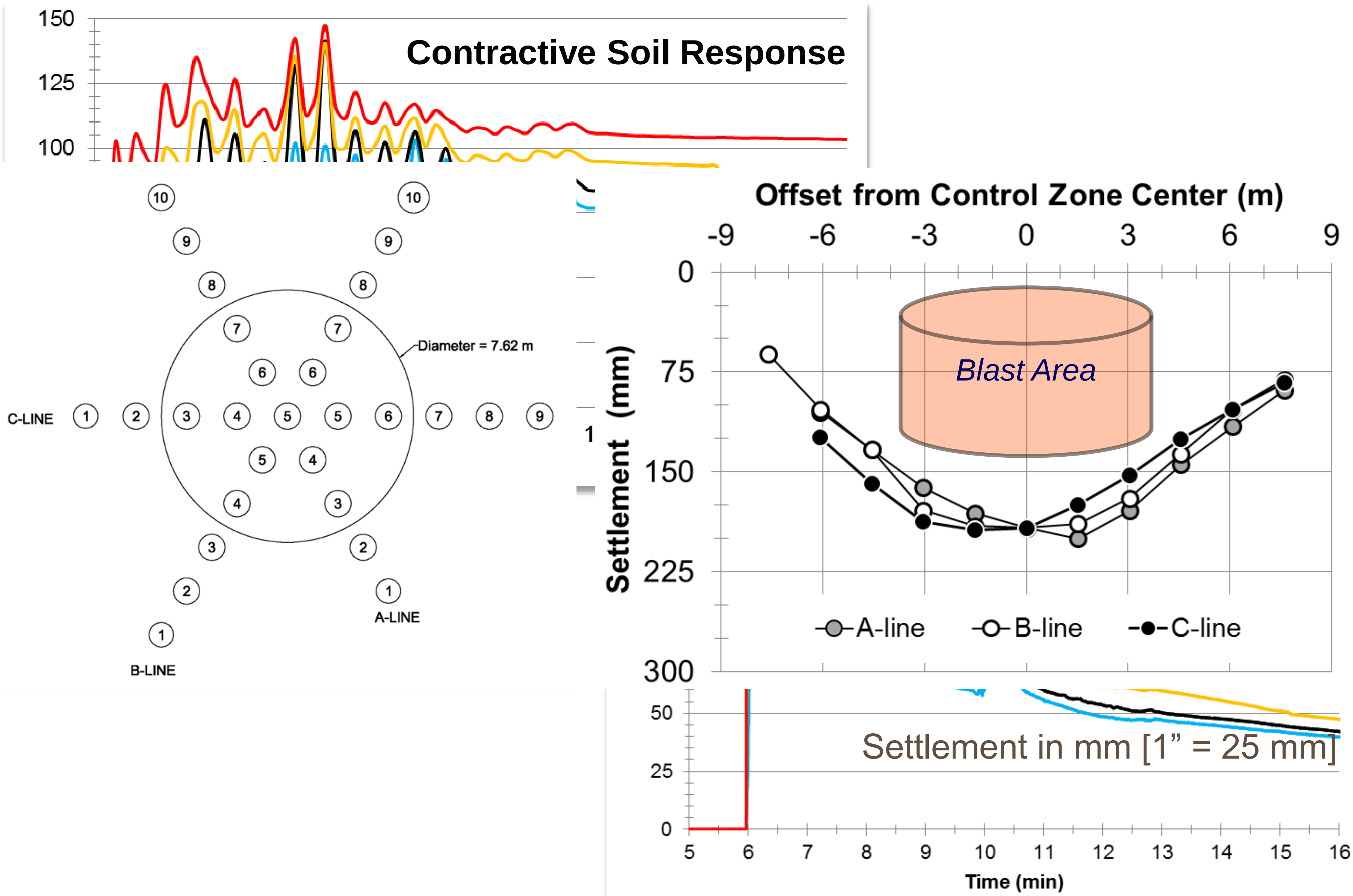
Controlled Blasting Program for the Control Zone



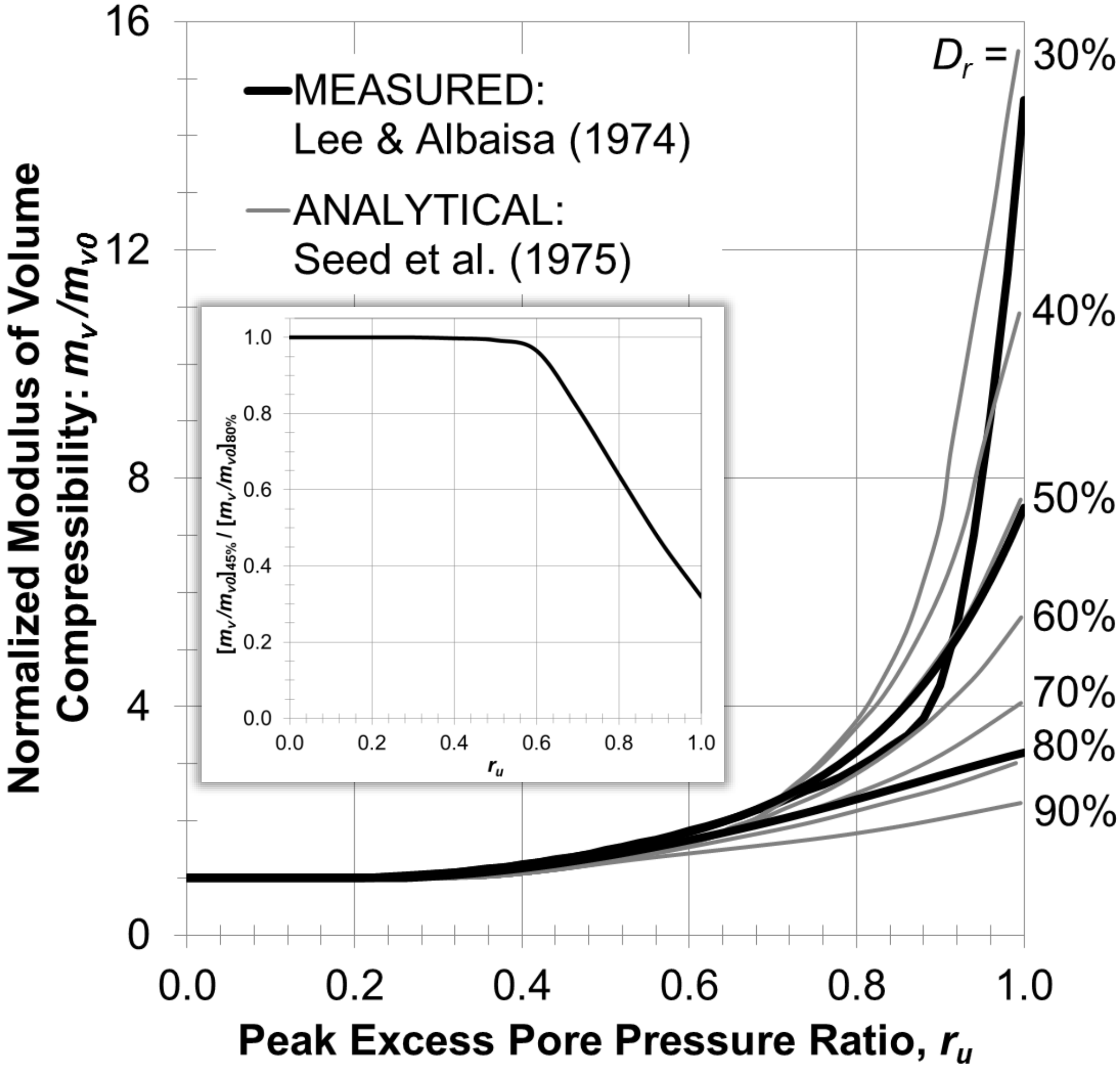


Controlled Blasting Program for the Control Zone

Controlled Blasting Program for the Control Zone

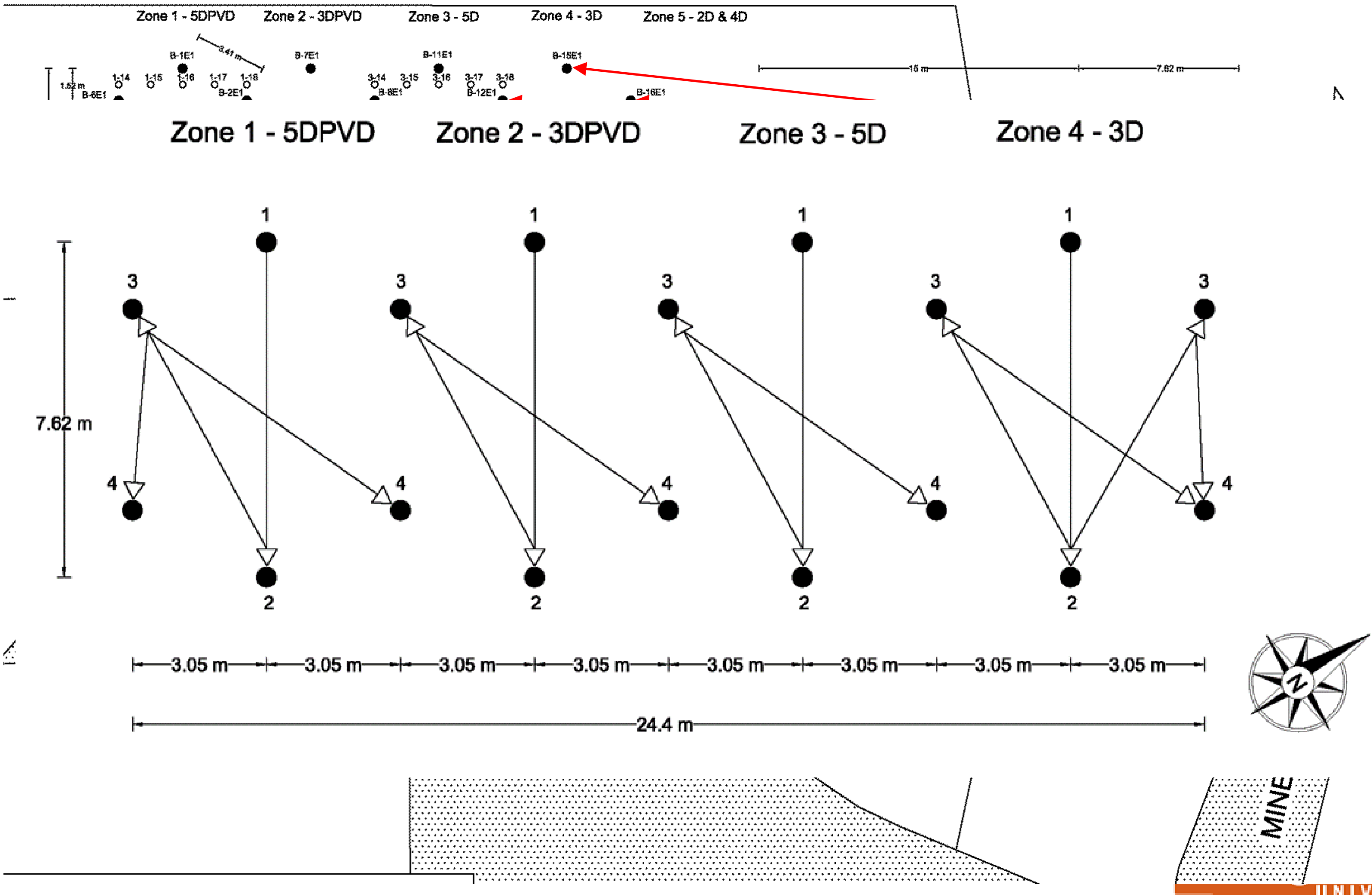


Mid-1970's: Assessment of Post-liquefaction Volumetric Strain



- From cyclic TX tests, we expect significant reductions in post-shaking settlements as D_r increases
- For an increase in D_r from 45 to 80%, we expect a 3-fold reduction in 1-D settlement

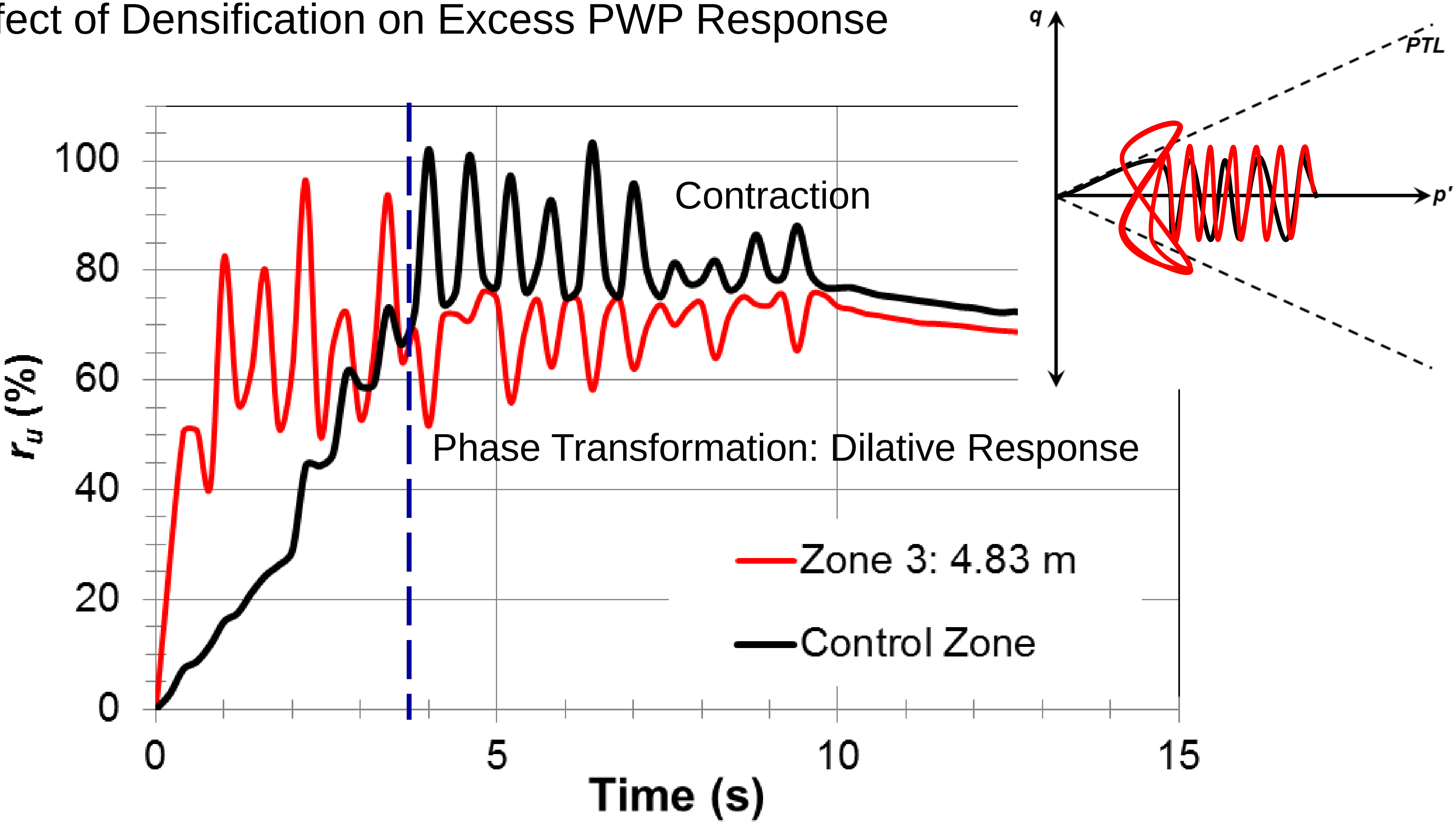
Controlled Blasting Program for the Treated Zones



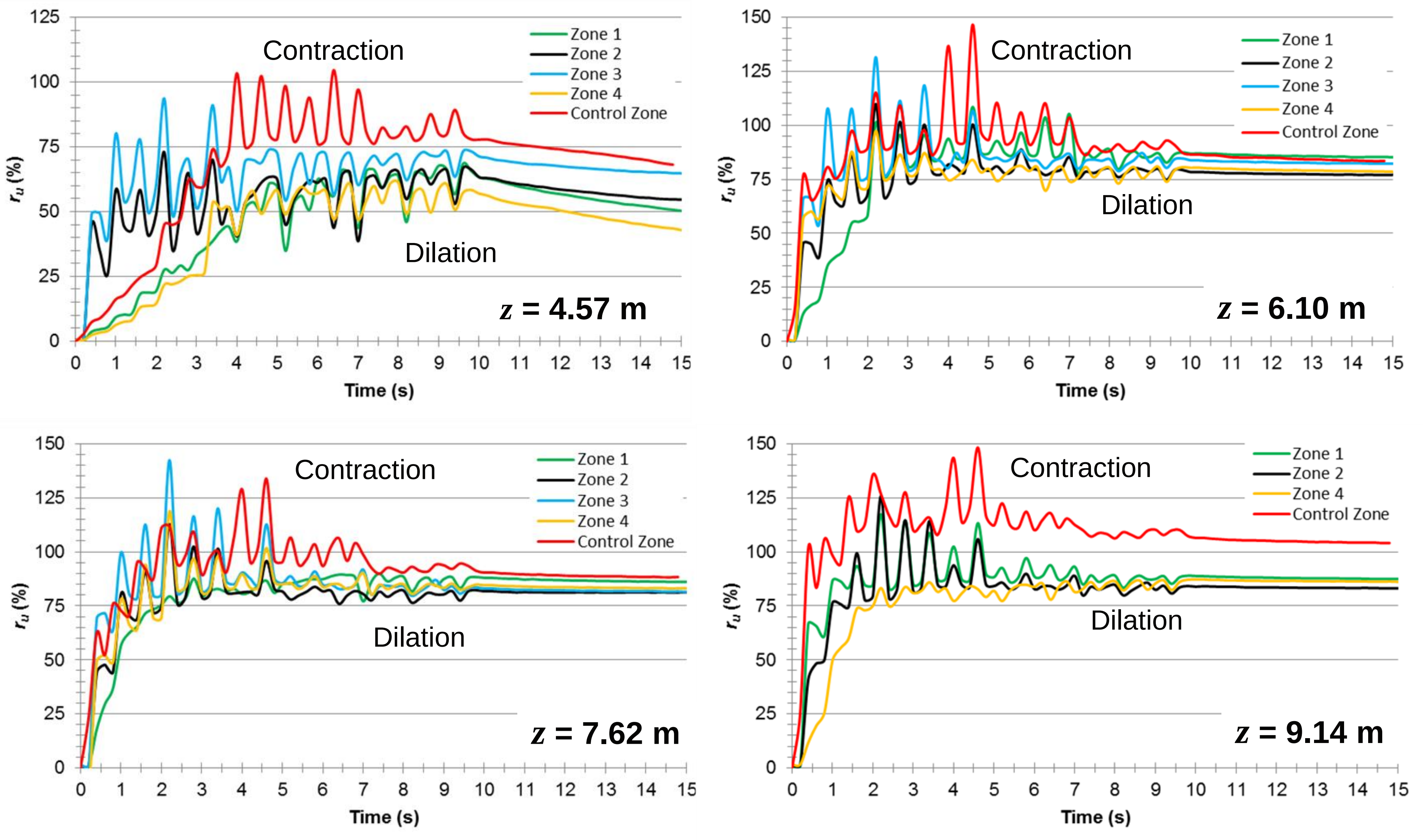
Controlled Blasting Program for the Treated Zones

Controlled Blasting Program for the Treated Zones

Effect of Densification on Excess PWP Response



Controlled Blasting Program for the Treated Zones

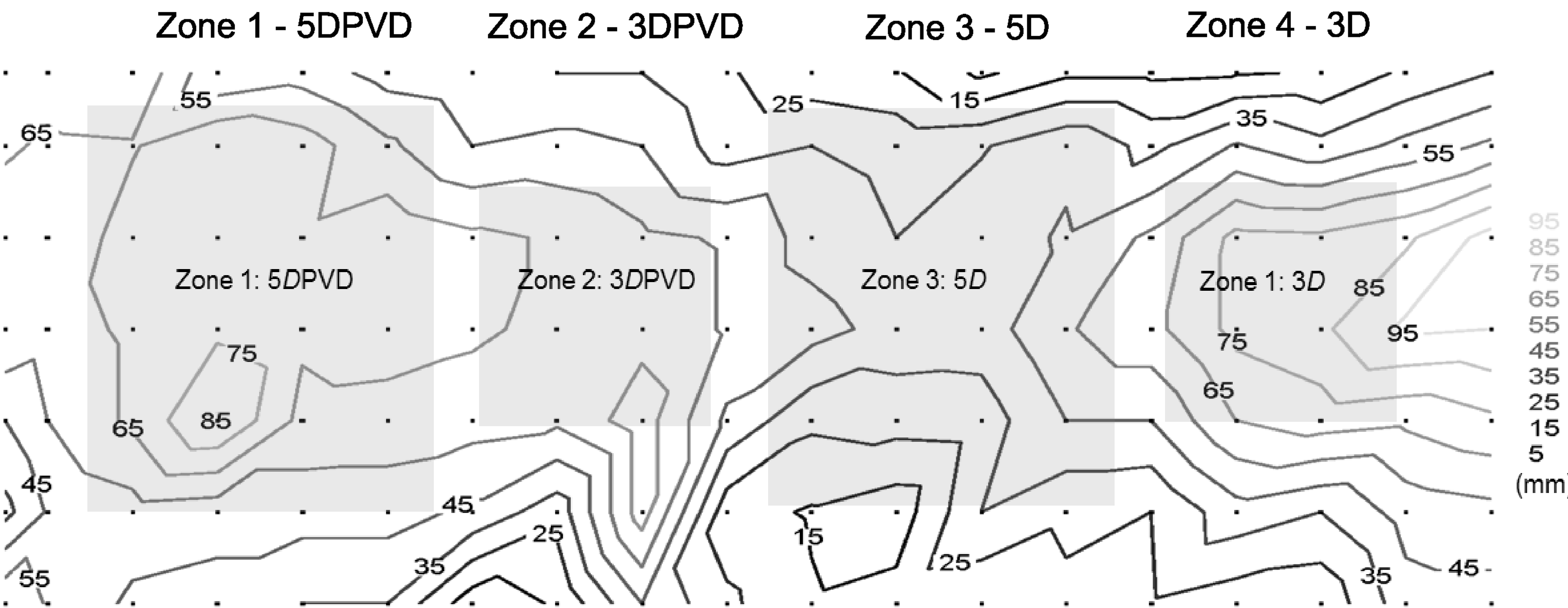


Controlled Blasting Program for the Treated Zones

Settlements = 1/6 to 1/3 that of control zone

These observations confirm the post-liquefaction ε_v measurements from the mid-70's

Median settlement of piles tipped in Dense Sand: 20 mm (3/4")



Settlement in mm [1" = 25 mm]

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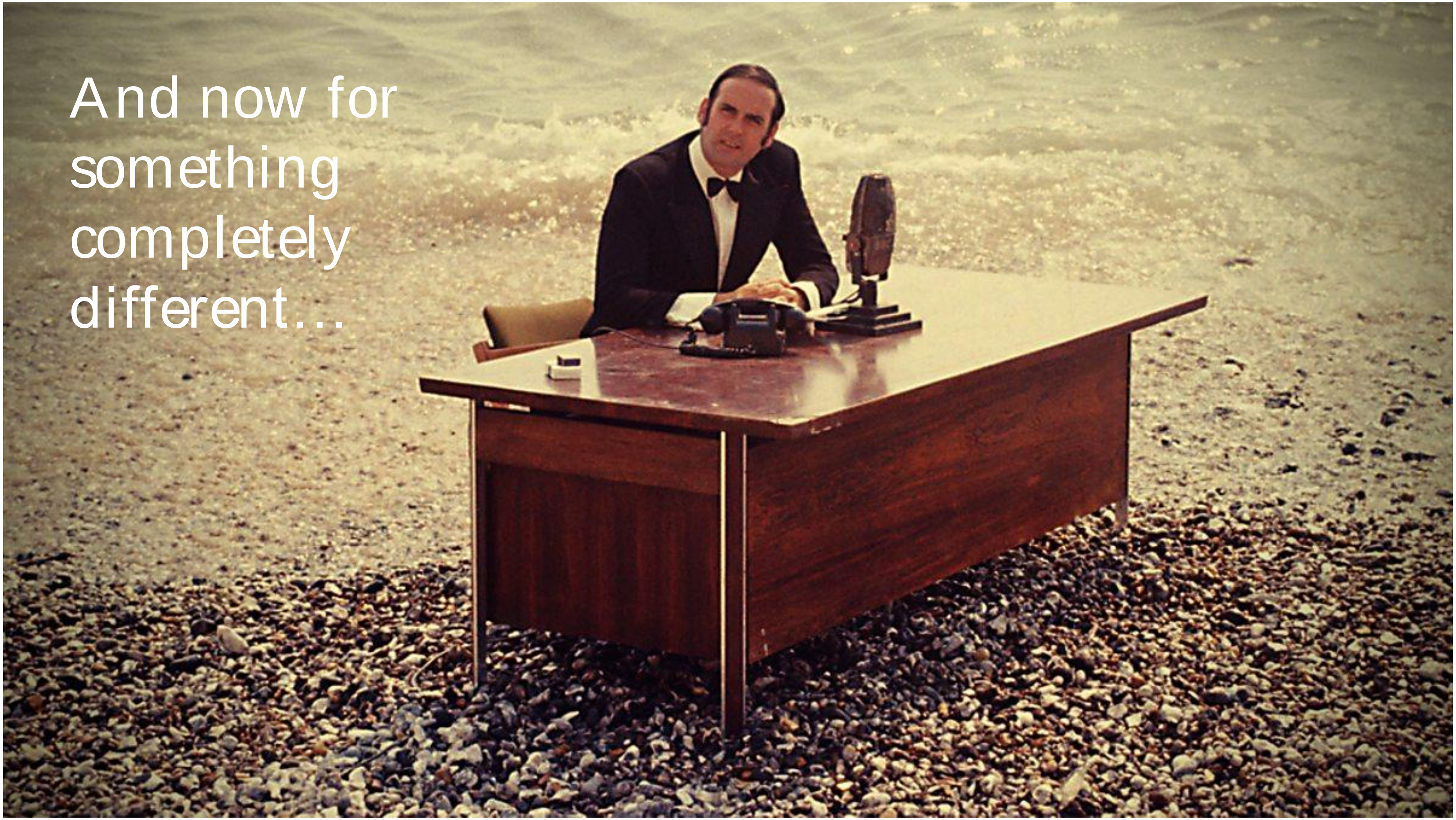
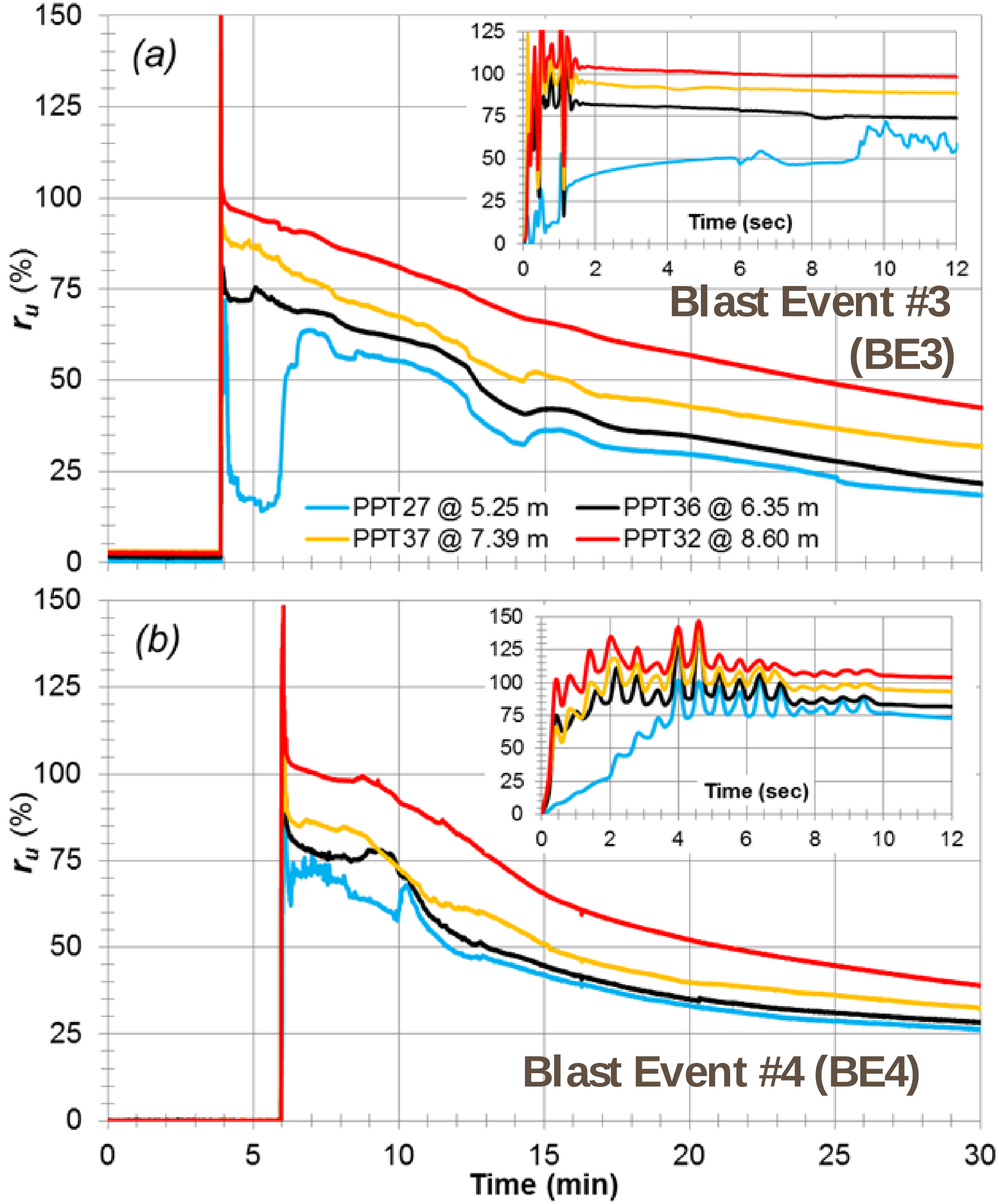
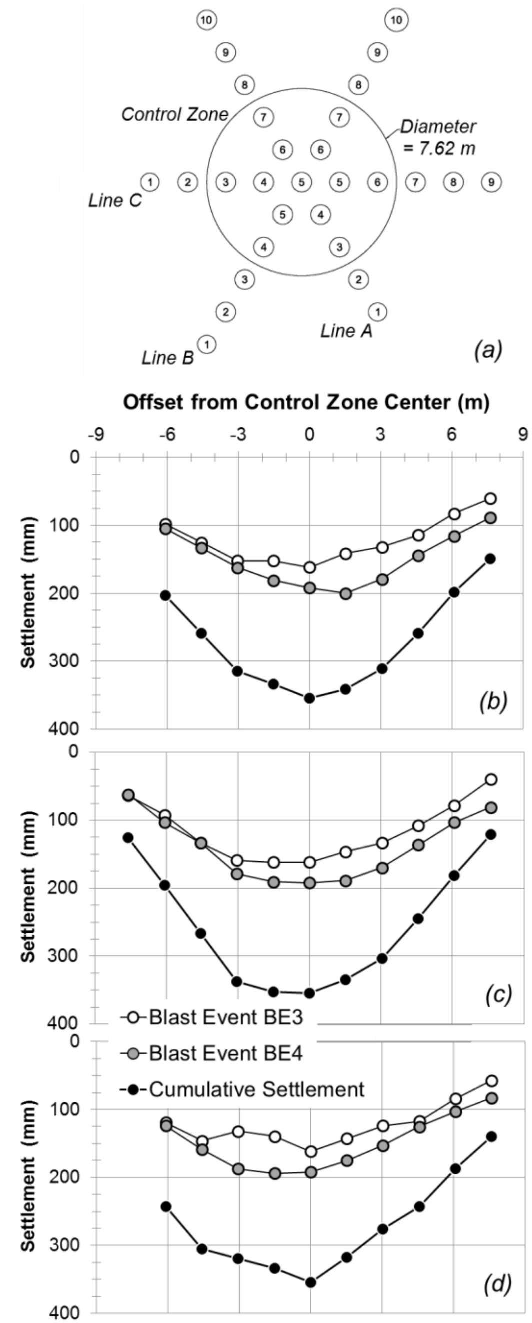
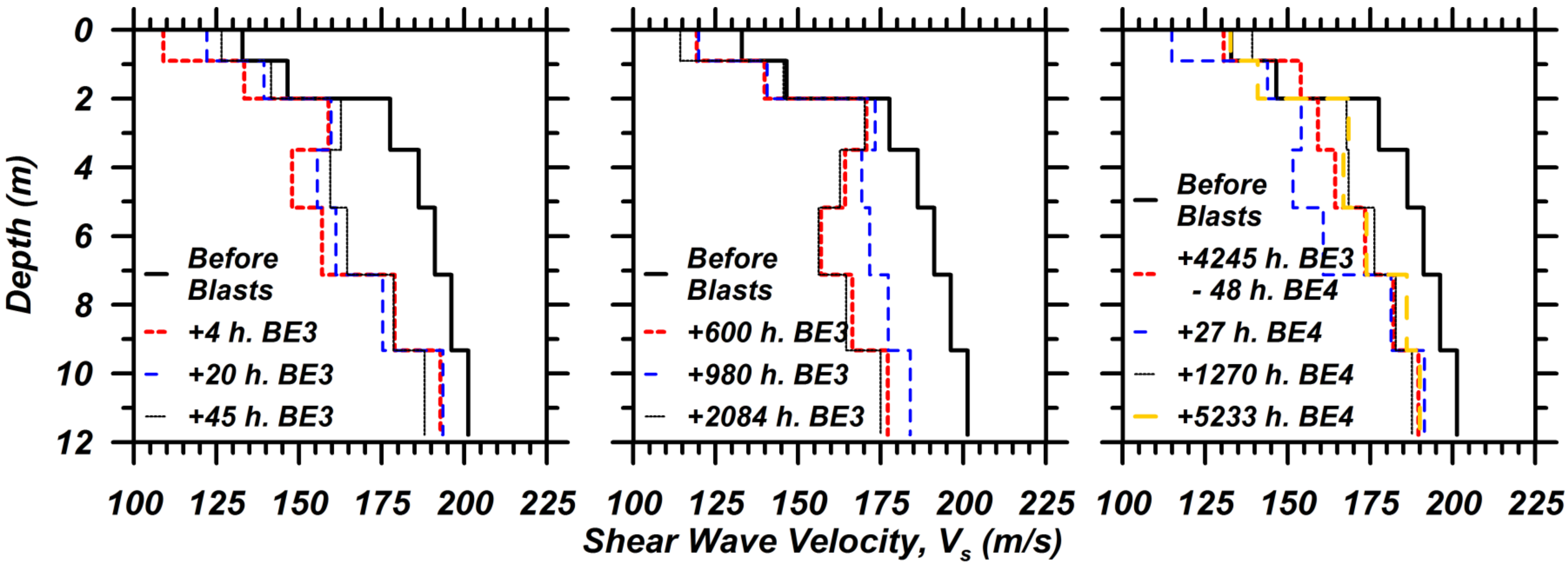

And now for something completely different...

Post-Blast Pore Pressures and Settlements

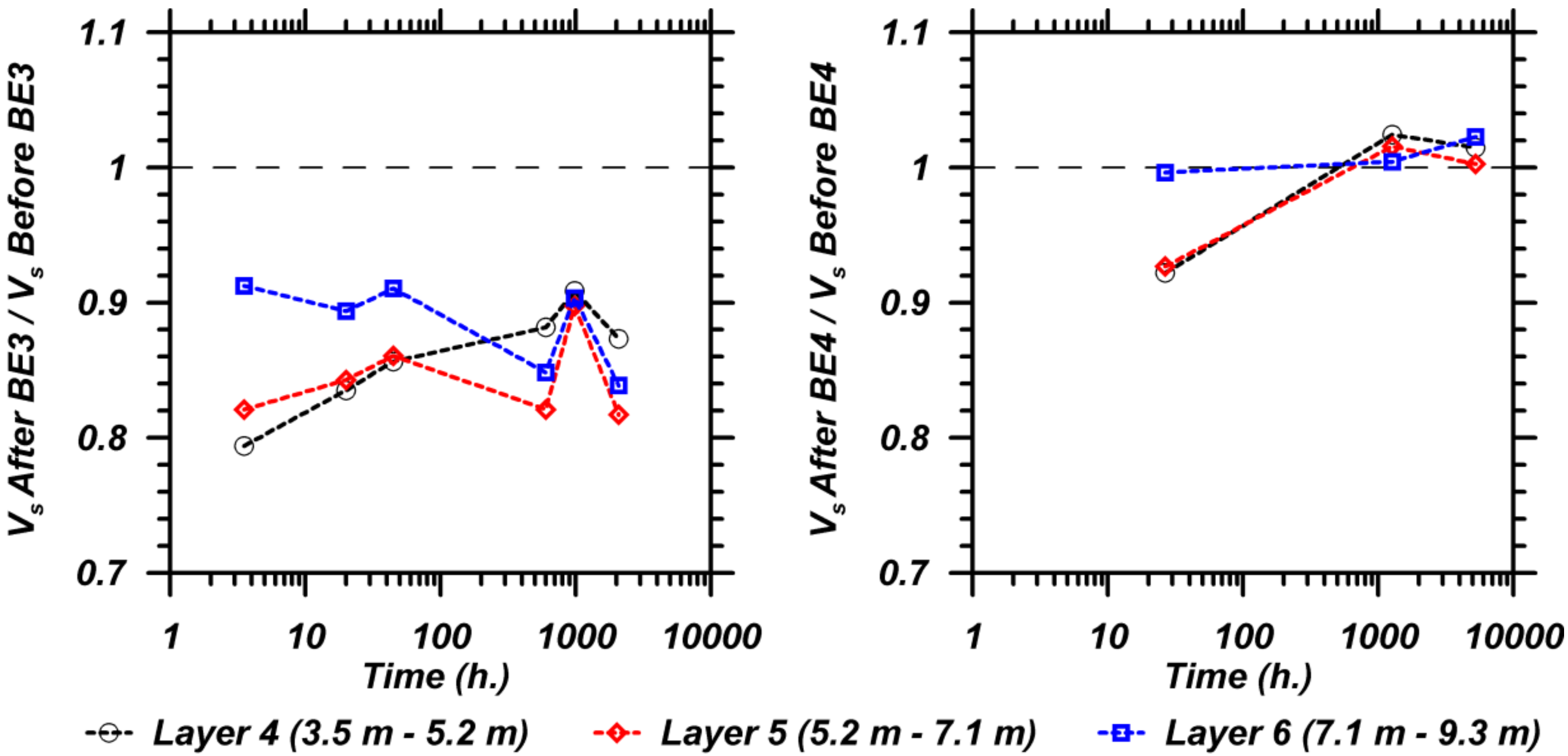




Pre- and Post-Blast V_s Profiles



Time Variation of Normalized V_s (Layers 4 – 6)



[Assessment of Reinforcement]

Reinforcement effect – Baez (1995) Approach

Baez (1995) shear strain compatibility (SSC) approach:
assuming the "simplified" method for liquefaction triggering

$$CSR = \frac{\tau}{\sigma'_{v0}} = 0.65 \cdot \frac{a_{\max}}{g} \frac{\sigma_{v0}}{\sigma'_{v0}} \cdot r_d \cdot MSF$$

substitute $\tau = \gamma G$ and rearrange for shear strain:

Note that MSF disappears for assessments of blast-induced shaking

$$\gamma_{SSC} = 0.65 \cdot \frac{a_{\max}}{g} \frac{\sigma_{v0}}{G_{comp}} \cdot r_d$$

$$G_{comp} = G_{soil}(1 - A_{rr}) + G_{pile} A_{rr}$$

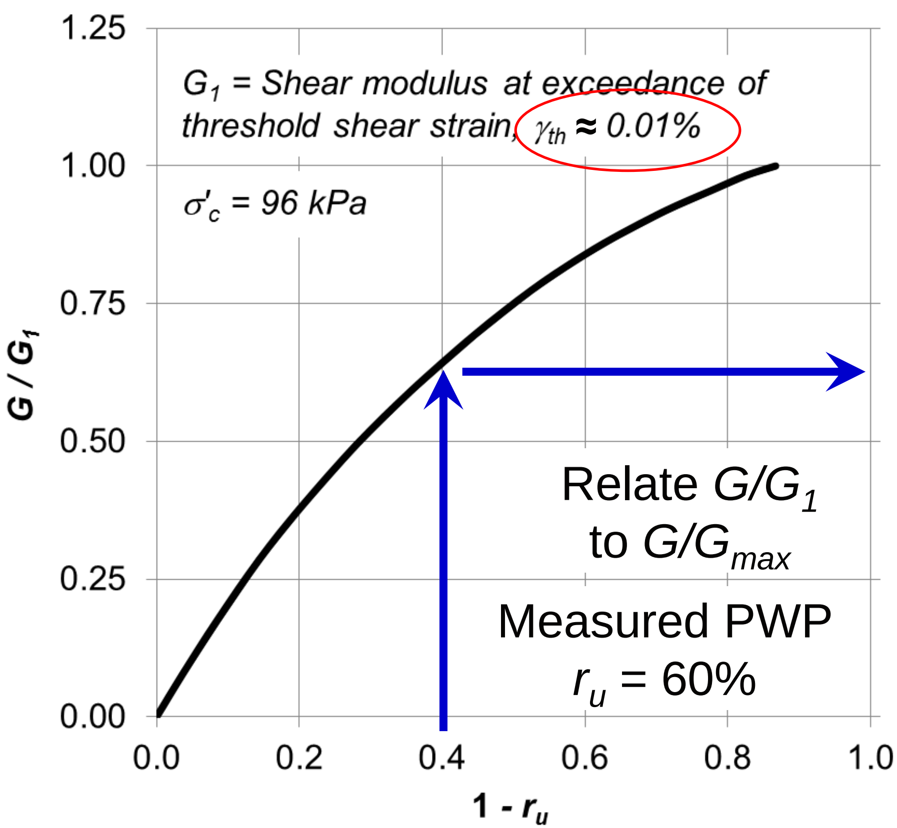
G_{comp} = shear modulus of composite ground

A_{rr} = area replacement ratio

*since $\mathbf{G_{pile}}$ >> $\mathbf{G_{soil}}$, small $\mathbf{A_{rr}}$ still provides high $\mathbf{G_{comp}}$, and theoretically small strains γ_{SCC}… If **SSC** assumption is appropriate….*

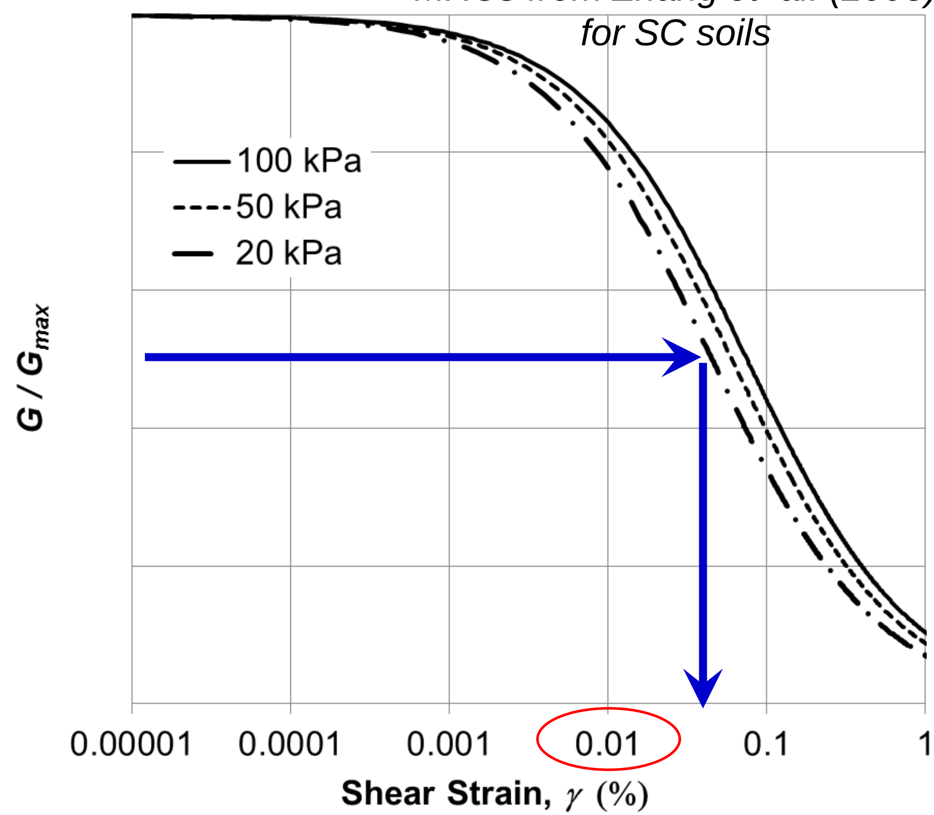
Reinforcement Effect – Estimation of Shear Strains

If we can estimate shear strains…we can make some observations on the reinforcement effect and the shear strain compatibility (**SSC**) assumption for reinforcement-type ground improvement

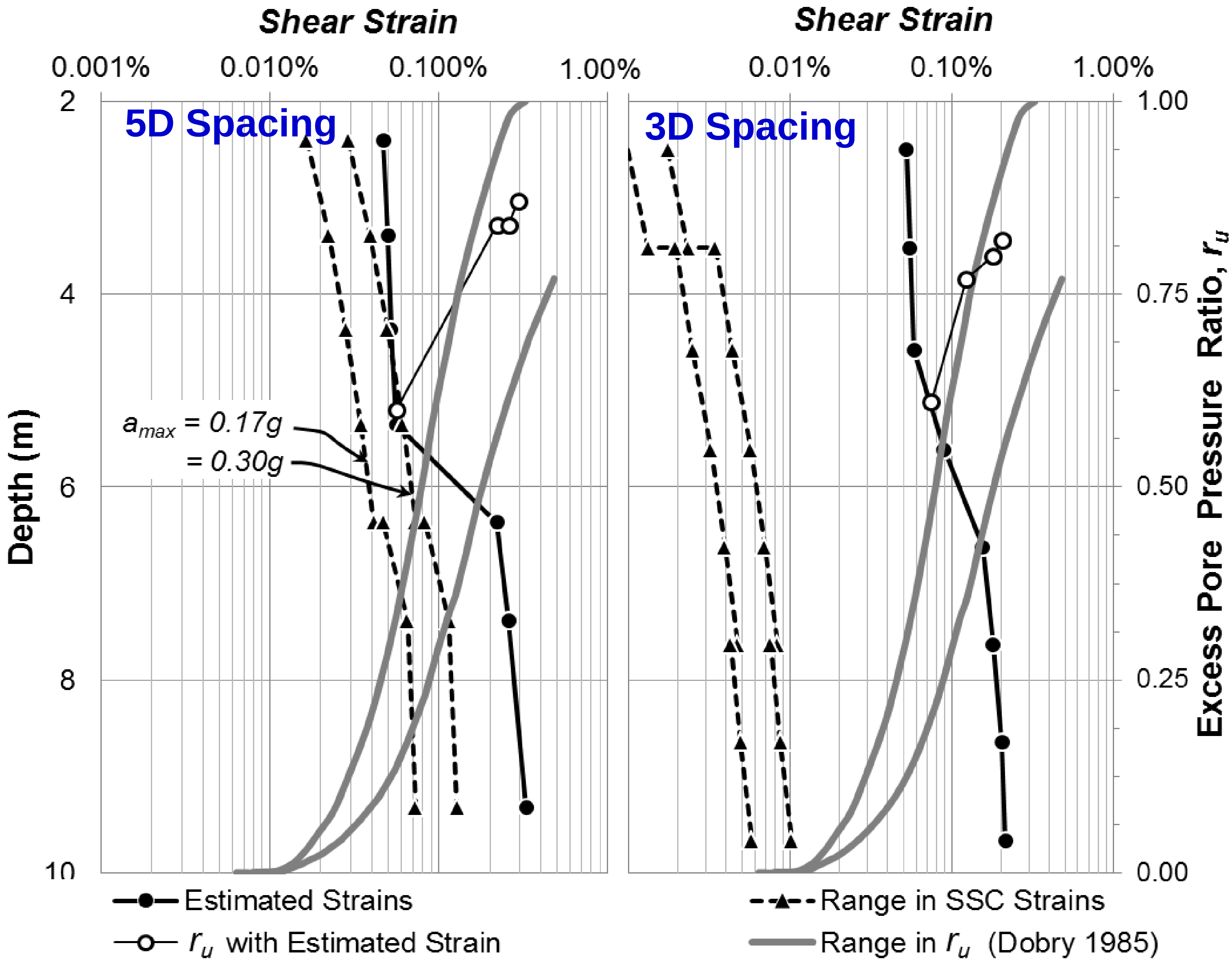


Curve based on Data by Dobry et al. (1982)

MRCs from Zhang et al. (2005) for SC soils



Reinforcement effect – Results of Assessment



Summary / Conclusions

Field Test Program

- Cone tip resistance increased 45 to 250%, immediately following installation of timber piles depending on the spacing (this corresponds to relative densities of 60 to 95% from 40 to 50%).
- Long-term observations suggested that relaxation of horizontal stresses occurred following installation of driven timber piles.
- Blasting performed in the control zone produced complete liquefaction for the deeper soils, resulting in maximum settlements of about 200 mm in the center of the control zone.
- Peak residual r_u values in the treated zone were all less than those of the unimproved ground, and produced dilative responses
- The average settlements observed in the improved zones were approximately one sixth to one third of the settlement observed for the same charge sequence applied to the unimproved control zone.
- Timber piles embedded in the dense sand layer had a median settlement of 20 mm compared to piles that were not tipped in the dense; these exhibited settlements similar to the reinforced soil

Summary / Conclusions

Analytical Investigations

- The finite element (FE) model prediction of generation and dissipation of excess pore pressures for conventional timber piles in Zones 3 and 4 were generally in good agreement
- The FE model over-predicted the pore pressure reductions in the drained timber pile zones – suggesting discharge capacity insufficient for dynamic use.
- The shear strain compatibility approach was found to under-predict the estimated shear strains experienced by the soil compared to those estimated based on measured excess pore pressure ratios in the field.
- Use of the shear strain compatibility approach is not recommended for use with discrete elements.

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Thanks to our Sponsors and Collaborators:

- **TRB IDEA Program of the National Academy of Science: Grant NCHRP-180**
- **PDCA of South Carolina**
- Van Hogan
- S&ME, Inc.
- SCI, Inc.
- Cox Wood Industries
- Pile Driver's Inc.
- Chuck Dawley Surveying
- Hayward Baker Inc.

Master's Student:

Tygh Gianella, Staff Engineer

GeoEngineers, Inc., Portland, OR

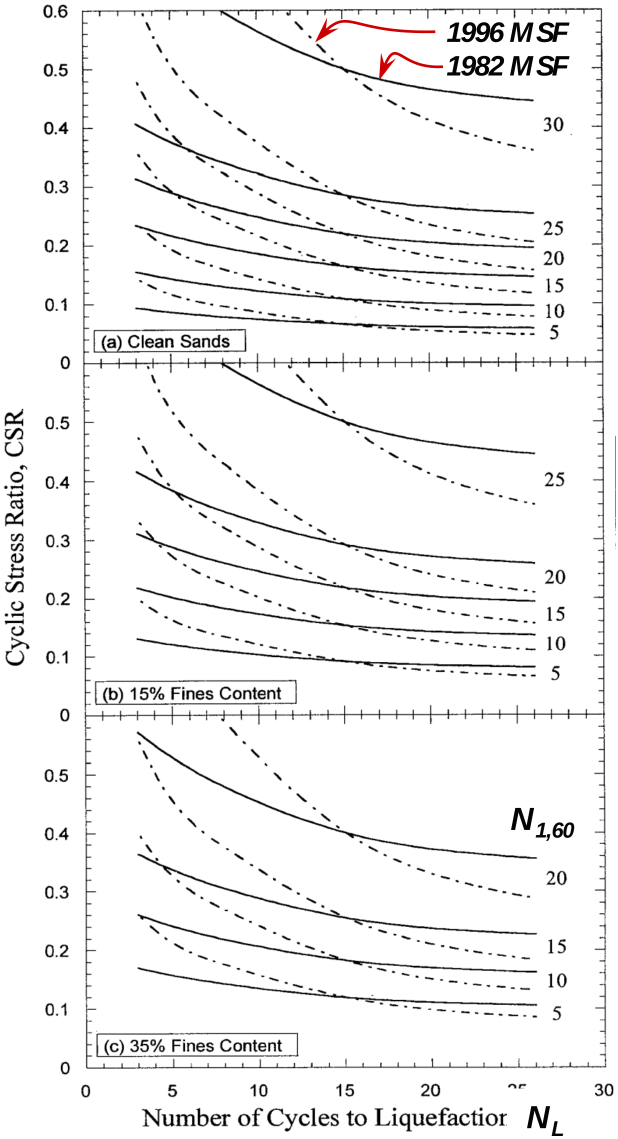
Gianella, T.N., **Stuedlein, A.W.**, and Canivan, G.J. (2015) "Densification of Liquefiable Soils using Driven Timber Piles," *6th International Conference on Earthquake Geotechnical Engineering*, Christchurch, New Zealand, 1 to 4 Nov. 2015. 9 pp.

Stuedlein, A.W., Gianella, T.N., and Canivan, G.J. (2016) "Densification of Granular Soils using Conventional and Drained Timber Displacement Piles," *Journal of Geotechnical and Geoenvironmental Engineering*, 04016075, ***Available Online***

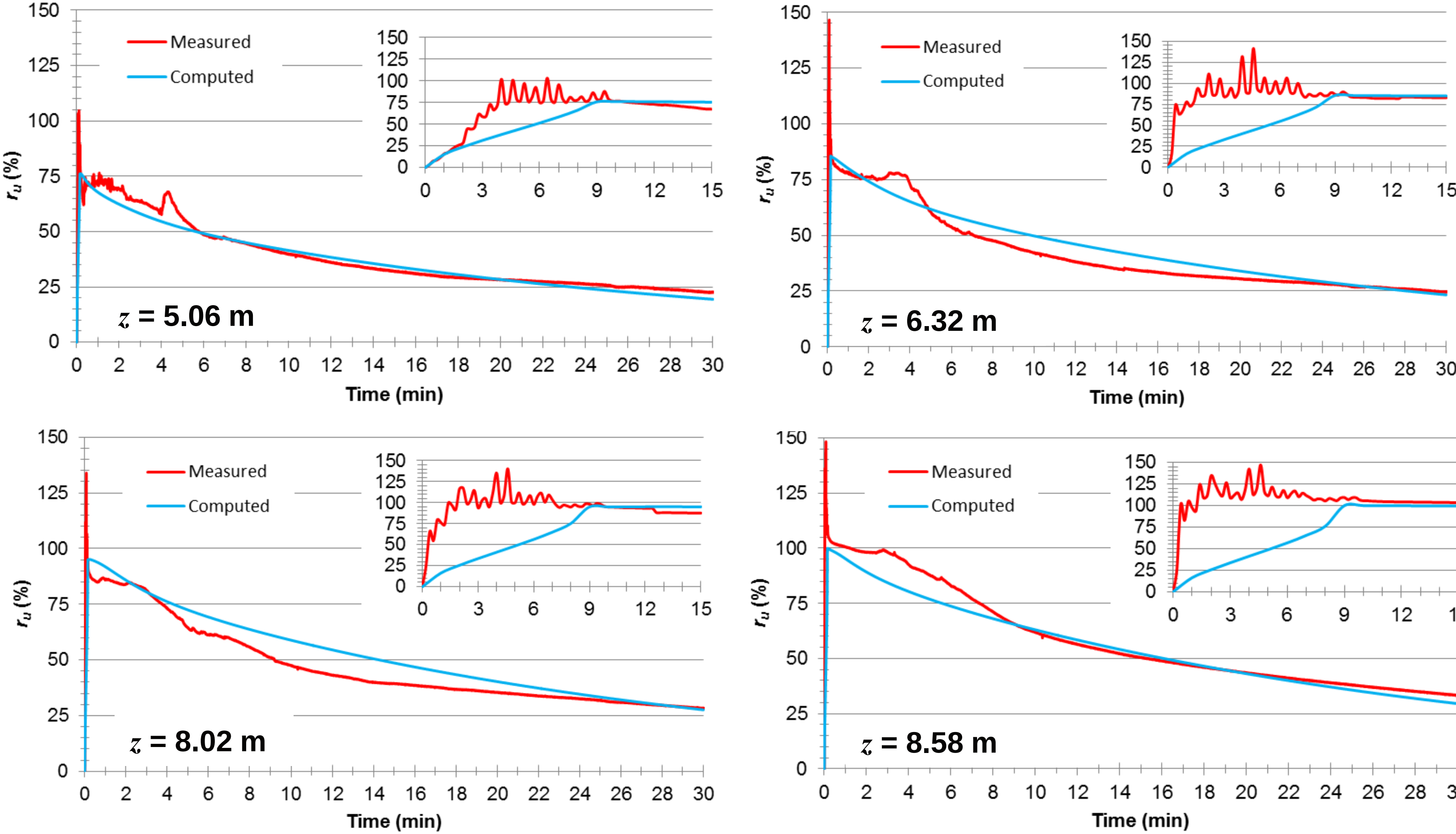
Gianella, T.N., and **Stuedlein, A.W.** (*In Re-Review*) "Performance of Driven Displacement Pile-Improved Ground in Controlled Blasting Field Tests," *Journal of Geotechnical and Geoenvironmental Engineering*, ***stay tuned…***

Analytical Investigations and Comparison to Controlled Blasting

- Finite Element Analysis: FEQDrain
  - Developed by Pestana et al. (1997)
  - Models earthquake-induced generation and dissipation of pore water pressure in layered sand deposits
- Input parameters
  - Earthquake loading parameters
    N_{eq}, t_d
  - Soil input parameters
    k_h, k_v, γ, m_v, N_L, D_r

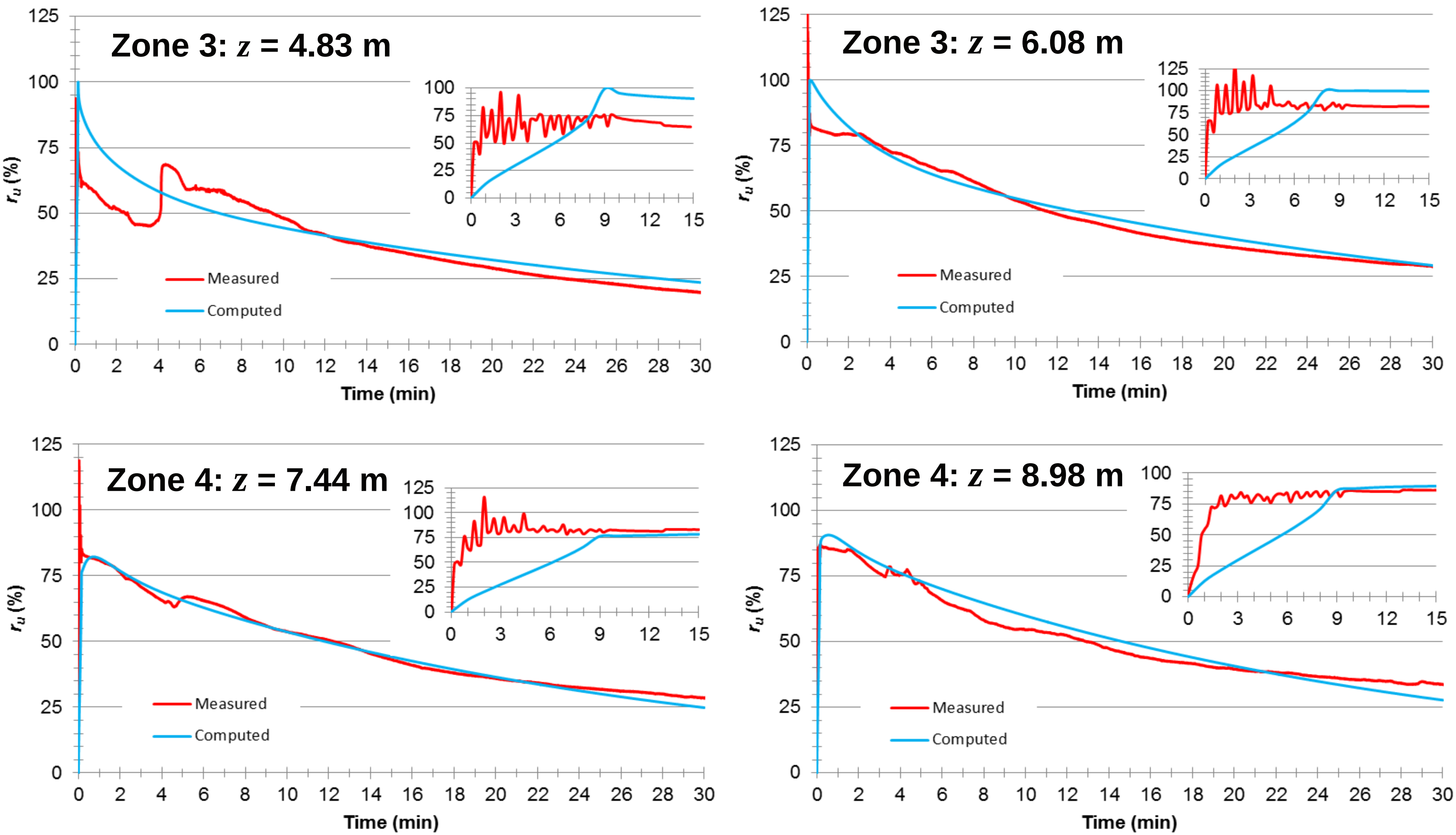


Calibrated Model: Generation and Dissipation of Excess Pore Pressure in the Control Zone



Treated Zone Response – Conventional Piles

NOTE: Only Relative Density and #Cycles to Liquefaction altered



Treated Zone Response – Drained Piles: Comparison of Measured and Computed Excess Pore Pressure